NASA Reference Publication 1146

November 1985

204P

Aeronautical Facilities Assessment

NASA

NASA
Reference
Publication
1146

1985

Aeronautical Facilities Assessment

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Washington, D.C.

National Aeronautics
and Space Administration

Scientific and Technical
Information Branch

PREFACE

A survey of the Western World's (non-Communist countries) aeronautical facilities was undertaken by the Office of Aeronautics and Space Technology (OAST) as a basis from which to assess NASA's capabilities and that of the U.S. in aeronautical R&D; particularly in relation to our competitors in the civil aviation market. This assessment is a continuing one aimed at underscoring where the principal facility strengths and weaknesses exist in NASA and the U.S. and where future emphasis must be placed to ensure continued excellence in the research development and testing of future aeronautical vehicles and systems, and this nation's competitive advantage in the civil aviation market. An important by-product of this survey was the compilation of a comprehensive aeronautical facilities catalogue that updated and expanded on similar efforts undertaken in the past by NASA and others.

This survey and assessment covers wind tunnels, airbreathing propulsion facilities, and flight simulators. The wind tunnels have been well documented in the past, although the latest survey was in 1976. Of the propulsion facilities, engine test stands have also been adequately covered in previous efforts, although propulsion component facilities have not. To the extent that this survey could determine, neither have flight simulations facilities. In all cases, moreover, foreign facilities have only been superficially covered, if at all, and very little attempt has been made to make a comparison and draw any judgement on the relative strengths and merits of these facilities nor where the premier capabilities exist. The present effort covers U.S. facilities in NASA, the DOD, industry, and academia, plus those of the Western World's nations and Japan. It also attempts to draw comparisons and offer an indication of the premier facilities in each of the above categories. In addition, this report includes an assessment of NASA's current strengths and weaknesses, plus a process for addressing its future needs through a long range facilities plan.

The information gathered in this survey was provided or verified by the individual facility owners or operators. Owners/operators were given the option to either include or exclude their facilities as they chose, within the criteria given them. Facilities that were identified as "standby" but still operable have been included in this assessment, since generally the criterion for "mothballing" a facility is based on workload (use) and not obsolescence or capability. It was assumed that any of these facilities can be reactivated within six months. On the other hand, those facilities that were clearly determined to be decommissioned, in a state of extensive disrepair, or dismantled have been excluded.

This report is structured into four major sections: one for each of the three facility categories covered (wind tunnel, airbreathing propulsion, and flight simulators) plus a fourth one addressing the state of NASA's own facilities and the outline for a long-range facilities plan, particularly in the aftermath of the Aero 2000 study. An executive summary, conclusions, and recommendations, plus appendices containing lists of facilities also are included. This is not intended as a technical report on aeronautical facilities, but rather as a management level summary containing enough technical background information on each facility to help the reader understand the conclusions and recommendations reached herein, and to put them in the proper perspective.

A team of experts from NASA and the DOD in each of the facility categories covered by the report was assembled to examine and evaluate the compiled information, and to provide the overall assessments for their respective classes of facilities. However, the specific assessment of NASA's capabilities and needs plus the conclusions and recommendations stated in this report are the sole responsibility of the undersigned, who is deeply grateful to the members of this team for their invaluable contributions.

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EXECUTIVE SUMMARY

A. BACKGROUND

A survey of the free world's aeronautical facilities was undertaken as a basis from which to assess NASA's capabilities in aeronautical R&D in relation to those of the DOD, U.S. industry, and other countries. This assessment was in part driven by urgings from the NRC's Aeronautics and Space Engineering Board (ASEB) and by NASA's Office of Aeronautics and Space Technology's (OAST) desire to address the question of whether NASA and the U.S. are adequately facilitated to conduct the caliber of aeronautical R&D necessary to preserve U.S. supremacy in military and civil aviation. Summary data from this survey have been included in this document, but more detailed information is available in a separately published Aeronautical Facilities Catalogue[1].

A recent report under the auspices of the Office of Science and Technology Policy (OSTP)[2] also addressed the issue of NASA's and the U.S. Government's role in Aeronautical R&D and its adequacy to face foreign competition. However, the question of adequate facilities throughout the U.S. to help meet this challenge was not sufficiently answered. This assessment attempts to fill that gap.

Another recent and related activity was the "Aero 2000 Study,"[3] designed to address the aeronautical technology needs of the year 2000 as a basis for determining the corresponding facility requirements, the adequacy of our current facilities to meet these requirements and/or the need to plan for either new or renovated facilities between now and then. That study plus the present survey/assessment also serve as the data base for building NASA's long range plans in this critical area.

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1. Aeronautical Facilities Catalogue, Vols I & II, NASA RP-1132 and 1133, 1985
2. Aeronautics R&T Policy, Office of Science & Technology Policy, Nov. 1982.
3. Aeronautics Technology Possibilities for 2000: Report of a Workshop. Aeronautics Technology & Space Engineering Board, National Research Council, 1984.

B. SCOPE

This assessment covers three of the four principal categories of aeronautical facilities that are considered the most crucial in developing and maintaining a preeminent aeronautical R&D capability and the healthy and competitive aviation industry it promotes. The three categories are:

- Wind Tunnels
- Airbreathing Propulsion Facilities
- Flight Simulators

The full spectrum of speed regimes in wind tunnels has been covered, ranging from subsonics through hypersonics. However, only the major facilities in each of these regimes have been considered. Small or pedagogical facilities were excluded. The propulsion facilities included altitude engine test stands as well as propulsion component facilities. Sea level test stands, because of their limited capabilities, were ignored. The flight simulators considered were those versatile enough to be used for research purposes. Trainers and small single purpose "cabs" were left out.

The fourth category, Numerical Simulation facilities (large computers), was left out of the current assessment because there are very few in existence or under construction and these are well known. The NASA Ames Numerical Aerodynamic Simulation facility (NAS) will be the premier facility in this category when it becomes operational in 1987. Central, general purpose ADP facilities or complexes, although essential in supporting aeronautical R&D, have not been included. Dedicated ADP/EDP mainframes, CPU's, etc., have been included as integral parts of the facilities they support, but have not been singled out as specific capabilities.

All the major installations of NASA and the DOD, U.S. industry, and academia were surveyed and covered in this study, as were the major foreign installations in the free world such as Canada, France, West Germany, the Netherlands, United Kingdom, and Japan. Good responses were received from wind tunnel owners/operators, domestic and foreign, and those are well represented. There is also good coverage of domestic propulsion and flight simulation facilities. However, foreign responses were only fair for engine test facilities and very marginal for component facilities or flight simulators.

C. SUMMARY FINDINGS

C-1 WIND TUNNELS:

About 200 wind tunnels meeting the criteria established for this assessment across all speed regimes were evaluated. Table I-a shows the distribution by speed regime and country. These figures indicate that the U.S. ownership of major wind tunnels far exceeds those of all other countries combined. This is also true for any individual speed regime, particularly hypersonics. The U.S. capital investment (replacement value) in these tunnels is at least $3 billion. No information on the foreign investment is available.

More important than sheer numbers, of course, is quality or capability. By this measurement also, the U.S. is judged to have the edge, particularly in the high speed tunnels. However, many foreign tunnels, being newer and incorporating the latest technology, are more productive and offer conveniences not found in the older U.S. facilities; principally in the subsonic tunnels. More specific observations are as follows:

a. Subsonic Tunnels: The U.S. (NASA) owns the two largest tunnels: Ames' 40x80x120 and Langley's 30x60; however, the Netherland's DNW offers large size, interchangeable test sections, and a very modern and productive facility. France's F1, the U.K.'s 5M, the Japanese 6M, and Canadian 30 ft tunnels are equally noteworthy.

Other than size, foreign facilities are quite comparable to the U.S.'s, although the latter has the edge in propulsion wind tunnels (NASA and industry) and in icing facilities, especially when the proposed Altitude Wind Tunnel at NASA Lewis comes on line around 1990.

b. Transonic Tunnels: With the initial operation of NASA Langley's National Transonic Facility (NTF), the U.S. clearly owns the superior Reynolds number capability in this speed regime. Moreover, it is also the leader in transonic propulsion and propulsion simulation facilities with NASA, DOD, and industry tunnels. The DOD is clearly the leader with AEDC's 16T facility.

The U.S.'s transonic tunnels are probably the busiest in the world, with Langley's 16T and Ames' 11ft tunnels having 2 to 3 year backlogs, and Calspan's excellent 8 ft facility as the U.S. industry's workhorse. Although not as heavily utilized as the U.S. tunnels, there are some very excellent foreign facilities in France's S-1, and the U.K.'s 8 ft tunnels.

Other than NASA Langley's NTF, reasonable Reynolds number capability in this speed regime is well distributed throughout the U.S. and foreign tunnels, with the group of 4 ft trisonic/polysonic tunnels being the leaders in this category. Although primarily concentrated in U.S. industry, the latter are also available in such countries as the U.K., India, Israel, Korea, and Taiwan, providing their owners with good capabilities. However, since these are high pressure, intermittent blowdown tunnels with short run duration, the larger continuous flow tunnels of Ames, Langley, and AEDC are the most utilized.

c. Supersonic Tunnels: Overall, this speed regime is well covered by domestic and foreign tunnels. The U.S. (NASA and DOD) owns the largest tunnels, while the U.S. industry has the highest Reynolds number capability, particularly in their 4 ft polysonic tunnels. Except for size, foreign tunnels are roughly comparable to the U.S.'s, providing average maximum Reynolds number capability. Supersonic tunnels are also very active, with considerable backlogs in the more popular facilities; especially the NASA Unitary Plan tunnels. However, many of these highly used facilities are getting very old and showing their age in maintenance and repair time. The Unitary tunnels (in particular) are over 30 years old and suffer from antiquated technology and low productivity.

d. Hypersonic Tunnels: One of the most neglected areas of research in recent years has been in the hypersonic speed regime, with the attendant impact on these research facilities. As a result, many hypersonic tunnels are now on standby or dismantled, principally in the U.S. industry. Nevertheless, the U.S. facilities still dominate this speed regime, whether in size, Mach number range, or maximum Reynolds number capability. Foreign facilities are much fewer in number and generally of lesser capability.

C-2 AIRBREATHING PROPULSION FACILITIES:

About 120 propulsion facilities covering the entire spectrum from propulsion wind tunnel, through engine test stand and components research facilities were surveyed and evaluated. Table I-b shows the distribution by category of facility and country, indicating a marked concentration of these facilities in the U.S., representing a capital investment (replacement value) of at least $3 billion. No comparable information on the foreign investment is available for propulsion facilities either, but there are some excellent engine test facilities in other countries; particularly in the U.K. On the other hand, very little information was made available on engine component facilities, and what there is indicates that the U.S. owns the preponderance of these facilities with little competition from abroad. The situation appears very similar in the case of propulsion wind tunnels. More specifically:

a. Propulsion Wind Tunnels: There are not many true propulsion wind tunnels available and as indicated above, these are mostly in the U.S.. The principal U.S. capabilities are at NASA Lewis and

DOD's AEDC. Canada, France, and the Netherlands are the only other countries with some notable capabilities in this area. Propulsion simulation tunnels, where high pressure air or exhaust is used to simulate the engine burn, were not considered in the comparison. The latter are used for propulsion/airframe integration research (aerodynamics), where the engine propulsion characteristics need only to be simulated. True propulsion/airframe research and testing capabilities that allow for real engine burns and provide the necessary environmental conditions (altitude and temperature variations in the full range of the flight envelope) are not available today in any of the free world's facilities. The proposed Altitude Wind Tunnel (AWT) facility at NASA Lewis is designed to fill this need in the high subsonic region.

b. Engine Test Facilities: These facilities were categorized into four groups according to mass flow, speed, and size: (1) high bypass, high flow, turbofan engines; (2) large turbojet, small high bypass, and low bypass turbofan engines; (3) medium and small turbojet engines; and (4) free jet facilities.

(1) High Bypass Turbofans: The premier capability exists in the U.S. at the Arnold Engineering Development Center's (AEDC) new ASTF facility. This American capability is backed by excellent facilities at Pratt & Whitney (E. Hartford). Outside the U.S., capabilities in the Western World are limited, with the only large facility in this category at the U.K.'s RAE-Pyestock Test Cell 3W. Based on the information obtained, the French do not appear to have a comparable capability. NASA does not have any capability in this category, and probably will not since this area is well covered by DOD and industry, and indications are that the direction of current research is toward high performance supersonic engines rather than large subsonic transport turbofan engines.

(2) Large Turbojets, Small High Bypass and Low Bypass Turbofan Engines: The premier capability for this class of facilities is also in the U.S., primarily at AEDC's ETF and ASTF facilities. This position is further strengthened by substantial capability in the U.S. industry (P&W and G.E.), and the U.S. Navy (NAPC) and NASA. Outside the U.S., France has a very good capability in Saclay (CEPr), and the U.K. at Pyestock.

(3) Medium and Small Turbojets: The capabilities in this category are evenly distributed throughout the Western World with no clear advantages evident in any single country.

(4) Free Jet Facilities: The largest free jet facility will be in the U.S. at AEDC when the ASTF free jet capability is operational around 1987. Other good U.S. capability exists at the Marquardt Company. In Europe, these facilities are primarily in England (7) and France (5), for a well distributed capability throughout the Western World. NASA does not own any free jet facilities, but instead relies on its large propulsion wind tunnels for this type of testing.

c. Propulsion Component Research Facilities: This category includes turbines, compressors, and combustor facilities, with the U.S. industry owning the major share of the world's capability, followed by NASA and DOD. Universities own mostly small-scale fundamental research facilities and rigs. The U.S. industry application of these facilities is mostly developmental and proprietary, while NASA's is for basic and applied research. Although the response from this survey by foreign installations was minimal, general knowledge of the foreign capability in component facilities indicates that except for the U.K.'s Rolls Royce and RAE-Pyestock facilities, this type of capability is limited in the other European countries. The Japanese, however, are building some impressive capabilities, particularly in the combustor research area. Despite the U.S. industry's overall supremacy in this category, NASA does own or is in the process of obtaining some unique research facilities, such as Lewis' High Pressure/Hot Section (HPF), Small Warm Turbine, and Large Low Speed Centrifugal Compressor facilities.

C-3 FLIGHT SIMULATORS:

Unlike other aeronautical facilities that have been around for decades, Flight Simulators, which depend very heavily on sophisticated electronic data and control systems, are a relatively young class of facilities and not as numerous as their wind tunnels or engine facilities counterparts. This is particularly evident with the R&D type of Flight Simulators on which this assessment focused. Of the roughly 85 candidate facilities reviewed, about 50, with a replacement cost of over $500 M, satisfied the criteria established for this survey and have been included in this evaluation. Most of these are in NASA and industry, with very few in foreign installations. Table I-c shows the distribution by owner. The U.S. is the undisputed leader in this category of aeronautical facilities, although some good capabilities exist in the U.K., France, Germany and Japan, with the latter currently building modern and very capable facilities. The U.S. leadership is generally across the board and resides mostly in the aircraft industry, although NASA owns the premier facilities in motion simulators with Ames' Vertical Motion Simulator (VMS) and Flight Simulator for Advanced Aircraft (FSAA).

Four classes of simulators were established for comparison: (1) Airborne Simulators; (2) High-Performance Aircraft (air-to-air) Simulators; (3) Vehicle-Specific Flight Decks; and (4) Generic Flight Decks. Pilot trainers and similar-type simulators such as those used extensively by airliners were excluded from this assessment.

a. Airborne Simulators: There are very few facilities classified in this category. The U.S. owns two exceptional ones with NASA Langley's Terminal System Research Vehicle (TSRV) and Calspan's

Total In-Flight Simulator (TIFS). The former uses a Boeing 737 and the latter a C-131 aircraft. The premier facility, however, appears to be the Advanced Technologies Testing Aircraft System (ATTAS), scheduled to be placed in operation by West Germany's DFVLR in 1986. This facility will have the combined capabilities of the TSRV and TIFS, plus the ability to simulate air traffic for ATC system studies.

b. High Performance (Air-to-Air) Simulators: These are primarily used for high-performance aircraft with large fields-of-view. McDonnell Douglas, St. Louis, has the best overall capability in this category with their Manned Air Combat Simulators (MACS). There are also significant capabilities in Germany, France, and the U.K. NASA's only capability in this area is Langley's DMS, which was one of the first simulators of this type and is now relatively obsolete.

c. Vehicle-Specific Flight Decks: As the title implies, these facilities are designed for the developmental needs of a specific type of aircraft, and therefore intercomparisons are very difficult. Nevertheless, Boeing is judged to have the best overall capability with current state-of-the-art system, followed by McDonnell Douglas. The Europeans also have excellent facilities in France and the U.K., and the Japanese are in the process of building some very good modern facilities.

c. Generic R&D Flight Decks: The majority of the R&D simulator facilities fall into this category. Comparisons in this group also are difficult because these facilities are usually designed to investigate a specific area of simulation such as motion, visual systems, ATC, etc.. Comparisons for each of these areas are given in the body of this report. Overall, NASA Ames has the best motion facilities with their Vertical Motion Simulator (VHS) and Flight Simulator for Advanced Aircraft (FSAA). Excellent visual capabilities employing the latest Computer Generated Imagery (CGI) systems with full-color capabilities are available at Ames and the major U.S. aircraft companies. In addition, the U.S. FAA owns the best ATC research facilities, with good capabilities also available at NASA (Ames and Langley).

This category of facilities is the most susceptible to obsolescence due to its critical reliance on continually advancing electronics and computational systems. The U.S. older facilities, therefore, are very vulnerable to being surpassed in capability by the newer ones being built overseas, particularly in Japan. For example, some NASA facilities at Ames (FSAA) and Langley (DMS) are over 10 years old and in serious need of upgrading.

C-4 NASA'S CAPABILITIES AND NEEDS

a. Wind Tunnels: Of the 39 major wind tunnels owned by NASA, 18 are considered World Class and 9 are at least National (U.S. Class) facilities. This capital investment, with a current replacement value of around $1.4 billion, represents a principal asset in the Nation's wind tunnel capabilities across all speed regimes. However, these premier facilities average about 30 years of age, and at least 11 (with a capital value of about $450 M) are in need of major rehabilitation or upgrading within the next 15 years; some as urgently as the next 5 years.

b. Airbreathing Propulsion Facilities: Almost all of NASA's airbreathing propulsion facilities (with a replacement value of about $690 M) are at Lewis. Only four are considered World Class: one wind tunnel and three propulsion component facilities. Lewis' principal engine test facility, the Propulsion Systems Laboratory (PSL), suffers from air flow limitations but is still of National quality. NASA's principal strength in this category is its overall research rather than test capability. Some major rehabilitation needs are also indicated for this group of facilities.

c. Flight Simulation Facilities: Of the 11 major flight simulators owned by NASA, with a current capital value of about $85 M, four are considered World Class and two more could be returned to that status with some rehabilitation or upgrading. These two are the FSAA at Ames and DMS at Langley, each about 15 years old. NASA's principal strengths in this field are its large motion systems and advanced research cockpits. However, in this rapidly advancing technology, facilities may become obsolete very rapidly unless constantly upgraded.

D. CONCLUSIONS AND RECOMMENDATIONS

The U.S. is clearly the current leader in aeronautical facilities with NASA, DOD, and industry playing significant roles across the three main categories of facilities. However, although the U.S. may be considered well facilitized today, some of its premier capabilities are quite old and will need rehabilitating/upgrading in the next few years. Careful attention also must be given to future requirements to meet the technology needs of the next century, so that today's preeminence in aeronautical R&D can be maintained. As a result of the current assessment and the Aero 2000 Study, NASA and the DOD are examining their respective facility needs for this timeframe and constructing Facility Long Range Plans. These plans will examine the need for upgrading current capabilities as well as constructing new ones. An eventual coordination of these plans between NASA, DOD, and industry advisors will be necessary to ensure that the country's future needs are properly addressed and satisfied.

The questions of facility deactivation and the role of test facilities versus numerical simulation methods also have been addressed. The opinion is that it is impractical to generate long range facility deactivation plans and that near term, almost ad hoc decisions (for reasons cited in this report) are more effective. It is also believed that numerical simulation methods will not attain the degree of sophistication and accuracy required to eliminate the need for large test facilities, nor for the basic research type. The continued role of the medium size wind tunnels, however, is questionable.

TABLE I-a

MAJOR WIND TUNNELS DISTRIBUTION

Location	Subsonic	Transonic	Supersonic	Hypersonic	Total
UNITED STATES	42	26 (6)	22 (6)	30	120 (6)
NASA	13	10	8	11	42
DOD	2	3	6	7	18
Industry	17	13 (6)	8 (6)	12	50 (6)
Academia	10	–	–	–	10
FOREIGN	34	22 (9)	16 (9)	9	81 (9)
Canada	3	1 (1)	1 (1)	–	5 (1)
France	5	6 (2)	3 (2)	4	18 (2)
Germany	4	4 (1)	2 (1)	1	11 (1)
Japan	7	5 (2)	3 (2)	1	16 (2)
Netherlands	2	1	1	–	4
United Kingdom	13	5 (3)	6 (3)	3	27 (3)
TOTAL	76	48 (15)	38 (15)	39	201 (15)

( ) Represents the number of Polysonic or multiple test section wind tunnels included as both Transonic and Supersonic.

TABLE I-b

AIRBREATHING PROPULSION FACILITIES DISTRIBUTION

	Wind Tunnels	Engine Facilities	Component Facilities	Total
UNITED STATES	7	42	46	95
NASA	4	4	18	26
DOD	2	16	3	21
Industry	1	22	23	46
Academia	-	-	2	2
FOREIGN	3	15	7	25
Canada	1	1	-	2
France	1	4	-	5
Germany	-	1	-	1
Japan	-	1	7	8
Netherlands	1	-	-	1
United Kingdom	-	8	-	8
TOTAL	10	57	53	120

TABLE I-c

FLIGHT SIMULATION FACILITIES DISTRIBUTION

	Airborne	High Perf. Aircraft	Vehicle Specific Flight Decks	Generic Flight Decks	Total
UNITED STATES	3	4	9	24	40
NASA	1	1	2	8	22
DOD	2	1	-	5	8
Industry	-	2	7	11	20
FOREIGN	3	4	2	3	12
Canada	1	-	-	-	1
France	-	1	-	-	1
Germany	2	1	-	1	4
Japan	-	1	2	1	4
Netherlands	-	-	-	1	1
United Kingdom	-	1	-	-	1
TOTAL	6	8	11	27	52

TABLE I-d

APPROXIMATE INVESTMENT IN U.S. AERONAUTICAL FACILITIES

($ B)

	Wind Tunnels	Propulsion Facilities	Flight Simulators	Total
NASA	1.4	.6	.11	2.11
DOD	1.1	1.8	.14	3.04
Industry	.4	1.1	.25	1.75
Academia	.1	-	-	.1
	3.0	3.5	.50	6.50

- These are approximate values stated in 1984 $.
- Estimates are conservative since they account only for those facilities covered in this assessment.
- Propulsion Facilities exclude wind tunnels but include an estimate for central air supply systems/facilities.

1. WIND TUNNELS

1.0 INTRODUCTION

About 200 wind tunnels meeting the established criteria across all speed regimes in the U.S. and throughout Western Europe and Japan were evaluated in this assessment. The speed regimes covered and the acceptance criteria were the following:

SPEED REGIME	MINIMUM TEST SECTION SIZE (ft)	MACH #
Subsonic	6	. 1
Transonic	4	-
Supersonic	2	1.2 - 3.5
Supersonic	1	3.5 - 5.0
Hypersonic	1	5.0

Only active or standby tunnels were considered. Decommissioned or mothballed facilities in need of major repairs for reactivation were not. Multiple speed tunnels, such as trisonic/polysonic tunnels and those having interchangeable nozzle and/or test sections to achieve several discrete speed ranges, have been included in each of the applicable speed regime groups (multi-listed). Refer to Table I-a for the distribution of the wind tunnels considered, by country/owner and by speed regime. Figures 1 to 4 show this comparison graphically.

Traditionally, comparison of wind tunnel test capabilities has been based primarily on size, Mach number, and Reynolds number range; characteristics which are readily available and quantifiable. The criteria used in the current assessment have, at least qualitatively, also considered other factors such as flow quality, productivity (rapid and efficient test section access and model preparation), instrumentation, etc., at least to the extent that this information is available or known by the Assessment Team members.

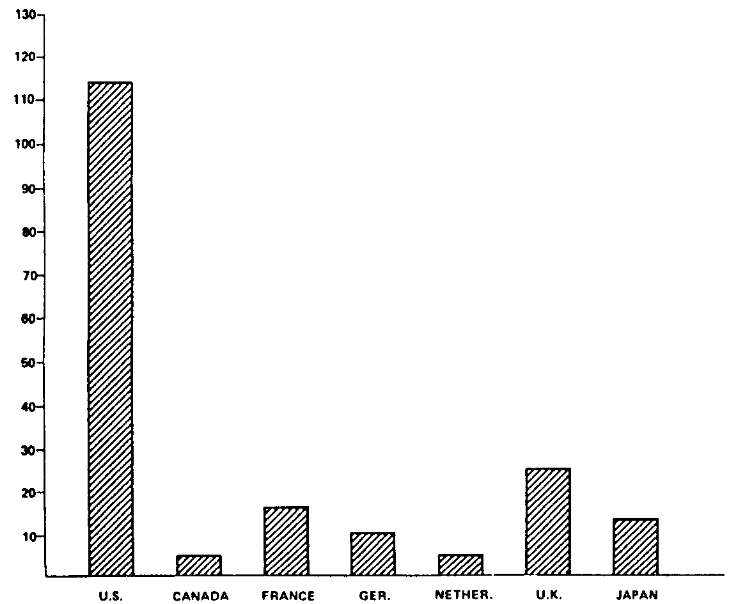


Figure 1. Total wind tunnel population by country.

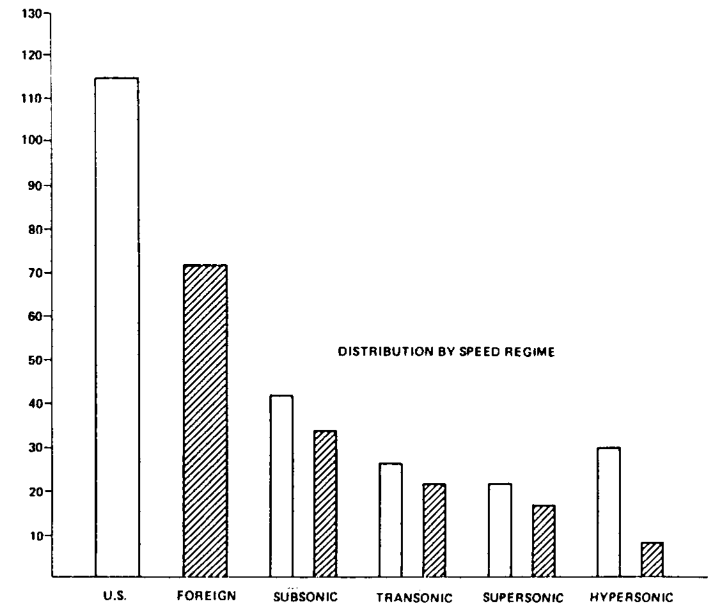


Figure 2. Total wind tunnel population (United States versus foreign).

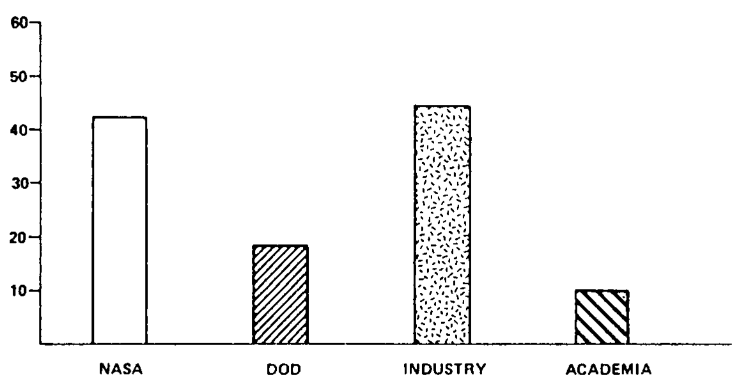


Figure 3. U.S. wind tunnel distribution by owner.

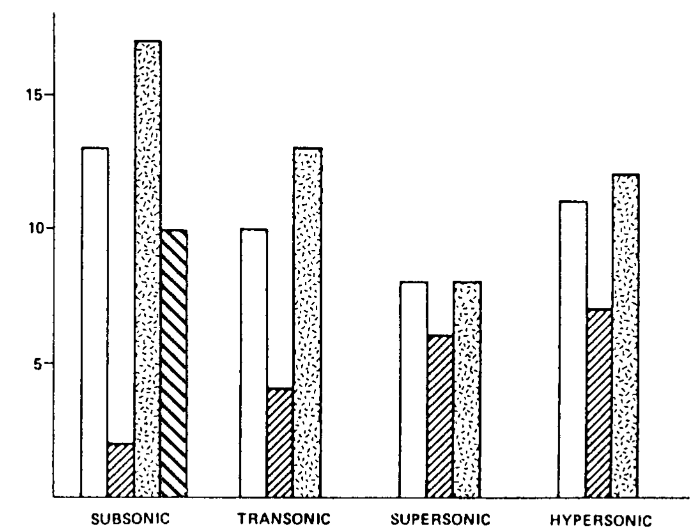


Figure 4. U.S. distribution by owner and speed regime.

SUBSONIC WIND TUNNELS
Premier Capabilities

	SIZE	$R_{e\ max}$	PROPULSION	SPECIAL FEATURES
NASA	ARC: 40 x 80 x 120 LRC: 30 x 60	ARC: 40 x 80 x 120 12 ft LRC: LTPT	ARC: 80 x 120	Icing: LeRC AWT (20 ft) IRT (9 x 6) Laser Vel.: ARC 40 x 80 x 120 LRC 4 x 7 m Pressure: ARC 12 ft; LRC LTPT Productivity: LRC 4 x 7 m Low Turbulence: ARC 12 ft; LRC LTPT
DOD				Flutter: David Taylor 8 x 10
U.S. INDUSTRY			Boeing: 9 x 9 Rockwell: 7 x 10 (simul) McD: 15 x 20 (simul)	Icing: Lockheed Icing Tun. (4 x 2.5) Flutter: Northrop 7 x 10 Rockwell (L.A.) NAAL Captive Traject: Vought 7 x 10
FOREIGN	Canada: 30 ft Japan: 6 m Neth: DNW (31 ft) U.K.: 5 m	France: F1 Germany: HDG KKK Japan: Cryogenic	Canada: 10 x 20 France: S-1 Neth: DNW	Laser Vel.: France F2 Pressure: German HDG; U.K. 5 m Cryogenic: German KKK; Japan Cryogenic Acoustics: France CEPRA 19; Neth. DNW Productivity: France F1; Neth. DNW; U.K. 5m Flutter: Japan Low Speed (TRDI; KHI)

Figure 5

TRANSONIC WIND TUNNELS
Premier Capabilities

	SIZE	$R_{e_{max}}$	PROPULSION	SPECIAL FEATURES
NASA	ARC: 14 ft 11 ft LRC: 16 ft TDT (16 ft)	ARC: 11 ft LRC: NTF TDT 0.3 m	LRC: 16 ft (simul)	Cryogenic: LRC NTF & 0.3 m Pressure: LRC NTF & 8 ft TPT MSFC 32 in. Laminar Flow: LRC 8 ft TPT Flutter Tests: LRC TDT
DOD	AEDC: 16 T	AEDC: 16 T	AEDC: 16 T	Captive Traject: AEDC 4 ft David Taylor 7 x 10
U.S. INDUSTRY		Calspan: 8 ft Lockheed: 4 ft Lockheed: Comp. Flow McD - Ca: 4 ft McD - StL: 4 ft Rockwell: 7 ft Vought: 4 ft	Grumman: 26 in (simul) Lockheed: Free Jet	Captive Traject: Calspan 8 ft; Vought 4 ft Acoustics: Rockwell 7 ft Pressure: Lockheed Compressible Flow; All 4 ft Cryogenic: McD 1 ft Flutter Tests: Grumman 26 in; Vought 4 ft Rockwell 7 ft
FOREIGN	France: S-1 (26 ft)	Canada: NAE France: S-1 Germany: 1 m (TWG) India: 4 ft U.K.: 8 ft Bedford 4 ft Warton	France: S-1	Captive Traject: India 4 ft Icing: France S-1 Cryogenic: France T-2 Flutter: U.K. 4 ft (Warton) Pressure: India 4 ft; U.K. 4 ft

Figure 6

SUPERSONIC WIND TUNNELS
Premier Capabilities

	SIZE	$R_{e_{max}}$	PROPULSION	SPECIAL FEATURES
NASA	ARC: 9 x 7 8 x 7 LeRC: 10 x 10 8 x 6		LeRC: 10 x 10 8 x 6	Captive Traject: ARC 9 x 7 8 x 7
DOD	AEDC: 16 S APTU	WAL: Mach 3	AEDC: 16 S APTU	Captive Traject: AEDC vK-A
U.S. INDUSTRY	Rockwell: 7 ft	Boeing: 4 ft Grumman: 15 in Lockheed: 4 ft McD - StL: 4 ft McD - Ca: 4 ft Rockwell: 7 ft Vought: 4 ft		Captive Traject: Vought 4 ft Acoustics: Rockwell 7 ft Pressure/Blowdown: All 4 ft
FOREIGN	France: S-2 (6 ft)	Canada: NAE Netherlands: SST India: 4 ft U.K.: 4 ft (Warton)		Captive Traject: India 4 ft Pressure/Blowdown: Netherlands SST; India 4 ft; U.K. 4 ft

Figure 7

HYPERSONIC WIND TUNNELS

Premier Capabilities

	SIZE	$R_{e_{max}}$	MACH NO.	SPECIAL FEATURES
NASA	ARC: 3.5 ft LRC: 8 ft HTT He 5 ft 4 ft Scramjet	LRC: Mach 6 Mach 20 He	LRC: He - 22 in. (20^+) Mach 20 He Nitrogen (18)	Propulsion: LRC 8 ft HTT 4 ft Scramjet Aerothermal: LRC 8 ft HTT
DOD	AEDC: vK - B&C NSWC: #9 (5 ft)	NSWC: #8 #9 WAL: Mach 6	NSWC: #8a (18) WAL: 20 in (14)	Captive Traject: AEDC vK - B&C Aerothermal: AEDC vk-C
U.S. INDUSTRY	Calspan: 96 in 48 in Grumman: 36 in	Calspan: 96 in 48 in	Calspan: 96 in (24) 48 in (20) Fluidyne: 20 in (14) Grumman: 36 in (14) Northrop: 30 in (14) Sandia: 18 in (14)	Propulsion: Gen. Applied Sciences Complex
FOREIGN	France: C-2 (4 ft)		France: C-2 (16)	

( ) Mach #

Figure 8

Only tunnels within each speed regime were compared. In some cases, as with the Subsonic group where the wind tunnel population is large, several subgroups were created to make the comparison more meaningful. Tables of these groups or subgroups, with the tunnels listed in a hierarchical order of capabilities, are included and discussed under each of the speed regime subsections. Additionally, a cross-index of all the tunnels, listed by installation and speed regime, is included in Appendices A to E.

1.1 SUMMARY ASSESSMENT

Overall, the U.S., through its various Government laboratories and aviation industry, has the superior capability in wind tunnel facilities. It owns the largest tunnels and those with the highest Reynolds number capability and broadest speed range. However, it also has the oldest and most antiquated facilities, in contrast to the newer, more productive tunnels of the Europeans.

Of the U.S. facilities, NASA's span the full spectrum of wind tunnels, with an emphasis on research capabilities where it is virtually unequaled. On the other hand, DOD's strength is based primarily on its large test facilities at AEDC, which are used principally for development rather than research purposes. The U.S. industry capabilities also lean heavily toward development and are often restricted for its owners' proprietary use. However, some facilities, such as Calspan's 8-ft. transonic tunnel, are widely used and have become the workhorses of the industry.

The Europeans have some very good facilities in the subsonic through supersonic range with their showpieces being the 5 meter tunnel in the U.K., the DNW complex in the Netherlands, and the F-1 in France. These facilities are all very modern and contain state-of-the-art technology and high-productivity features. Generally, they are well facilitated in all the speed regimes except hypersonics. In the transonic region, they are attempting to generate a consortium of nations for the purpose of building a European equivalent of the NTF, which would be called the ETW (European Transonic Wind Tunnel). However, this project is still in the negotiation stages and is at least 5 to 10 years in the future.

Although the U.S. currently holds the overall advantage in these facilities, many of the most utilized ones (such as NASA's Unitary Plan tunnels) will be nearly 50 years old by the year 2000. Considering the 10 to 15 years it takes from the conceptual to the operating stages of these large and costly facilities, serious attention must be given now to the future of the Nation's existing tunnels and to plans for either rehabilitating them or building new ones within the next 15 years if the U.S. is to hold its competitive edge. This is especially true in the high-speed tunnels, particularly Hypersonics.

Figures 5 to 8 summarize the premier facilities in each of the speed regimes with respect to size, Reynolds number capability, Mach number range, propulsion, and special features.

1.2 SUBSONIC WIND TUNNELS

Of the hundreds of subsonic wind tunnels in the world today, most are small with characteristic test sections smaller than 6 feet (~2 meters) and speeds less than Mach 0.2. While it is recognized that many of these facilities are used for fundamental research and/or pedagogical purposes, they do not represent the principal capabilities in low speed aeronautical R&D, and with few exceptions, have not been included in this assessment. Also, most of these tunnels have been grouped and evaluated mainly according to size and speed, although tunnels with special features such as propulsion, icing and pressure capabilities have also been identified and compared separately.

Ten groups based on the above criteria were created to differentiate those tunnels having sufficient commonality to be characterized as comparable. All tunnels were accommodated within one of the given groups, and except for those listed as having acoustical test capabilities, no tunnel appears in more than one group. Moreover, the tunnels within each group have been listed in decreasing order of capability (mainly size).

Group	Characteristics
A	>30 Ft
B1	12 - 30 Ft; Max Mach #>0.2
B2	12 - 30 Ft; Max Mach #<0.2
C	8 - 12 Ft
D	>8 Ft
E	Pressurized
F	Propulsion
G	Vertical Spin
H	Acoustical Test Capabilities
J	Unique Features

GROUP A: In this group of the largest wind tunnels in the world, the U.S. owns all facilities. The Ames 40x80x120 complex is the major V/STOL and helicopter test facility, while the Langley 30x60 tunnel permits full scale general aviation aircraft testing and provides a unique "free-flight" tethered model testing capability.

GROUP B1: This group of large sized tunnels represents modern, state-of-the-art facilities built to support powered, V/STOL model tests and to obtain force and moment measurements. The Netherland's DNW tunnel is the premier facility in this category, capable also of providing acoustic testing and good flow characteristics for flow field surveys and vortex flow measurement. The Langley 4x7 meter and the Boeing-Vertol 20x20-ft tunnels also offer good flow qualities, followed by the Lockheed-GA 16x23-ft and the Japanese NAL tunnels. The U.S. and foreign capabilities are about equal in this category.

GROUP B2: These tunnels are similar in size to those in B1, but with speeds usually less than Mach 0.1. Many of these are actually V/STOL test sections built in tandem with smaller test sections where the bulk of the tunnels' work is conducted (Group C). Flow quality for these big tunnels is generally poor and their overall capabilities are not considered critical in the U.S./foreign technology balance.

GROUP C: This very large group of moderate sized tunnels provides the "workhorse" facilities for industry's unpowered model configuration test and development and for government/university fundamental investigations. While there are many capable facilities in this group, these are uniformly spread in the U.S. and abroad, and no particular facility or capability clearly rises above the others.

GROUP D: This group of more modest facilities is representative of the very large population of small subsonic tunnels in the world today. These are generally of moderate cost, available mostly in academic institutions and small research establishments, and do not represent unique or premier facilities. These too are evenly distributed between foreign and domestic installations with no clear advantage on either side.

GROUP E - PRESSURE TUNNELS: The tunnels listed in this group represent the most advanced subsonic wind tunnels with respect to flow quality, Reynolds number, and generally versatile test capability. The premier facilities are the French ONERA F-1, the United Kingdom's RAE 5 meter, and the NASA Ames' 12-ft tunnels. The French and British tunnels have an edge in that they are more modern and capable of higher productivity due to their more efficient test section set-up and rapid change features. The Ames' 12 ft is one of the most heavily utilized facilities but has very cumbersome model/experiment preparation procedures and is in need of rehabilitation with more modern equipment and test section access features. The foreign capabilities are superior to the U.S. capabilities in this category.

GROUP F - PROPULSION TUNNELS: These three facilities represent the subsonic members of a very small group of "true" propulsion wind tunnels (those able to handle the combustion products of real engine burns, as opposed to propulsion "simulation" tunnel where engine air flow is simulated with high pressure air). The U.S. owns the best capabilities in this category, but this capability is very limited. A larger, higher speed altitude simulation facility is necessary to conduct full scale, complete propulsion system/airframe integration research and testing. This is especially crucial in the development of sophisticated propulsion/airframe systems such as those of future V/STOL or turboprop aircraft.

GROUP G - VERTICAL FLOW SPIN: These are very specialized facilities, few in number and distributed evenly among the U.S., France, and Japan.

GROUP H - ACOUSTICAL TEST CAPABILITIES: This list represents those tunnels in the other groups that have the capability to perform acoustical (noise) experiments through either removable or permanent acoustical treatment of the test section and/or tunnel walls. These facilities are particularly important in V/STOL and turboprop R&D. This capability is broadly distributed abroad and domestically.

GROUP J - UNIQUE FEATURES: This list includes tunnels whose unique capabilities warrant special consideration. The features listed are principally cryogenic or icing capabilities. The former is a rare feature in subsonic tunnels, while the latter is a rare and specialized feature, period. There are very few icing facilities in the free world and NASA Lewis' Icing Research Tunnel is the largest and most capable. The French S-1 in Modane can be adapted with an icing mechanism, but being an atmospheric tunnel it depends on cold weather for its ice-making capabilities. This is at best an uncertain feature with noncontrollable, nonreproducible conditions. Table II list the tunnels in each of the above groups.

TABLE II

COMPARABLE SUBSONIC TUNNELS

Facility Name	Installation
GROUP A (>30 ft)	
80 x 120-ft	NASA–Ames
40 x 80-ft	NASA–Ames
30 x 60-ft	NASA–Langley
GROUP B1 (12-30 ft; Mach >0.2)	
S-1 MA	France–ONERA, Modane
20 x 20-ft V/STOL	Boeing Vertol
4 x 7-m	NASA–Langley
6-m Low Speed Tunnel	Japan–National Aerospace Laboratory
DNW	Netherlands–Netherlands Research Laboratories
Large Subsonic	United Technologies Research Center
Low Speed (TS #1)	Lockheed–Georgia
GROUP B2 (12-30 ft; Mach <0.2)	
9 x 9-m	Canada–National Research Council
18-ft	United Kingdom–BA, Warton
15 x 20-ft V/STOL	Vought
15-ft	United Kingdom–BA, Hatfield
16 x 20-ft V/STOL	General Dynamics–Convair Division
Large Ground Effects Facility	Vought
Low Speed Wind Tunnel TS #2	Lockheed–Georgia
Mini Speed or Interim V/STOL	McDonnell Douglas–St. Louis
Subsonic Wind Tunnel with V/STOL	Rockwell–Columbus

	Facility Name	Installation
	GROUP C (7 x 10-12 ft; Continuous Flow)	
	11.5 x 8.5-ft	United Kingdom–RAE, Farnborough
	Large Subsonic	United Technologies Research Center
	13 x 9-ft Low Speed Tunnel	United Kingdom–BAc, Weybridge
	13 x 9-ft	United Kingdom–RAE, Bedford
	3.5-m	Japan–KHI
	10 x 12-m	United Kingdom–BAc, Filton
	3.25 x 2.8-m (NWB)	Germany–DFVLR, Braunschweig
	10-ft Subsonic Tunnel	GALCIT–California Institute of Technology
	9 x 9-ft	Canada–National Research Council
	3 x 3-m (NWG)	Germany–DFVLR, Gottingen
	9 x 7-ft Low Speed Tunnel	United Kingdom–BAe, Woodford
	8 x 12-ft	General Dynamics Convair
	8 x 12-ft	Lockheed–California
	8 x 12-ft	University of Washington
	8 x 10-ft	DOD–David Taylor
	7 x 10-ft (1)	NASA–Ames
	7 x 10-ft (2)	NASA–Ames/Army
	7 x 10-ft	NASA–Langley
	7 x 10-ft	Northrop
	7 x 10-ft	Vought
	7 x 10-ft	Texas A & M University
	2 x 3-m	Canada–National Research Council
	Convertible Tunnel (TS #1)	Japan–TRDI
	Low Speed Wind Tunnel	McDonnell Douglas–St. Louis
	Low Speed Wind Tunnel	Japan–TRDI
	NAAL	Rockwell–Los Angeles
	Subsonic Wind Tunnel	Rockwell–Columbus
	S2-CH	France–ONERA, Chalais-Meudon

	Facility Name	Installation
	GROUP D ($\leqslant$ 7 x 10 ft)	
	7 x 10-ft	Grumman
	7 x 10-ft	Wichita State University
	7 x 9-ft	Georgia Institute of Technology
	7 x 9-ft	United Kingdom–BAc, Hatfield
	7 x 5-ft Low Speed Tunnel	United Kingdom–BAc, Brough
	2.7 x 2.1 Low Speed Tunnel	United Kingdom–BA, Warton
	2-m Low Speed Tunnel	Japan–Mitsubishi
	4 x 6-ft	United Technologies Research Center
	3 x 2-ft High Speed Tunnel	United Kingdom–BA, Weybridge
	Low Speed Wind Tunnel	Japan–Fuji Heavy Industries
	Low Speed Research Tunnel	Boeing–Seattle
	Low Turbulence Tunnel	Georgia Institute of Technology
	LST 3 x 2.25-m	Netherlands–Netherlands Research Laboratories
	Subsonic Wind Tunnel	University of Oklahoma
	Wright Brothers Tunnel	Massachusetts Institute of Technology
	GROUP E–PRESSURE TUNNELS	
	5-m Low Speed Tunnel	United Kingdom–RAE, Farnborough
	F1	France–ONERA, Le Fauga
	12-ft Pressure Tunnel	NASA–Ames
	Low Turbulence Pressure Tunnel	NASA–Langley
	High Pressure Tunnel (HDG)	Germany–DFVLR, Gottingen
	GROUP F–PROPULSION TUNNELS	
	20 x 10-ft	Canada–National Research Council
	9 x 15-ft **(For Propulsion Component)**	NASA–Lewis
	9 x 9-ft A & B	Boeing–Seattle

Facility Name	Installation
GROUP G–VERTICAL FLOW SPIN TUNNELS	
20-ft Vertical Spin Tunnel	NASA–Langley
SV4	France–ONERA, IMF/Lille
Convertible Tunnel (Test Section 3)	Japan–TRDI
Vertical Wind Tunnel	DOD–Wright Aeronautical Laboratories
GROUP H–ACOUSTIC	
40 x 80-ft	NASA–Ames
24-ft Low Speed Tunnel	United Kingdom–RAE, Farnborough
DNW (6 x 6-m)	Netherlands–NRL and DFVLR
18/8-ft Large Subsonic	United Technologies Research Center
4 x 7-m	NASA–Langley
9 x 15-ft with V/STOL	NASA–Lewis
7 x 10-ft	NASA–Ames
CEPRA 19	France–ONERA, Saclay
Acoustic Tunnel	Massachusetts Institute of Technology
GROUP J–UNIQUE FEATURES	
Cryogenic Tunnel (KKK)	Germany–DFVLR, Koln-Porz
Cryogenic Tunnel	Japan–University of Tsukuba
6 x 9-ft Icing Research Tunnel	NASA–Lewis
Icing Wind Tunnel	Lockheed–California
6 x 6-ft Stability Tunnel	Virginia Polytechnic Institute
F2	France–ONERA, Le Fauga

TABLE III

HIGH REYNOLDS NUMBER SUBSONIC TUNNELS

Tunnel	Location	$R_e c \times 10^{-6}$
Low Turbulence Pressure	NASA–Langley	30
40 x 80 ft	NASA–Ames	17
High Pressure (HDG)	Germany–Göttingen	12
12-ft Pressure	NASA–Ames	10
80 x 120	NASA–Ames	9.8
Cryogenic	Japan–Tsukuba	9.8
5 m	U.K.–RAE Farnborough	7.8
KKK	Germany–DFVLR, Köln-Porz	7.8
F1	France–ONERA Fauga	7.3

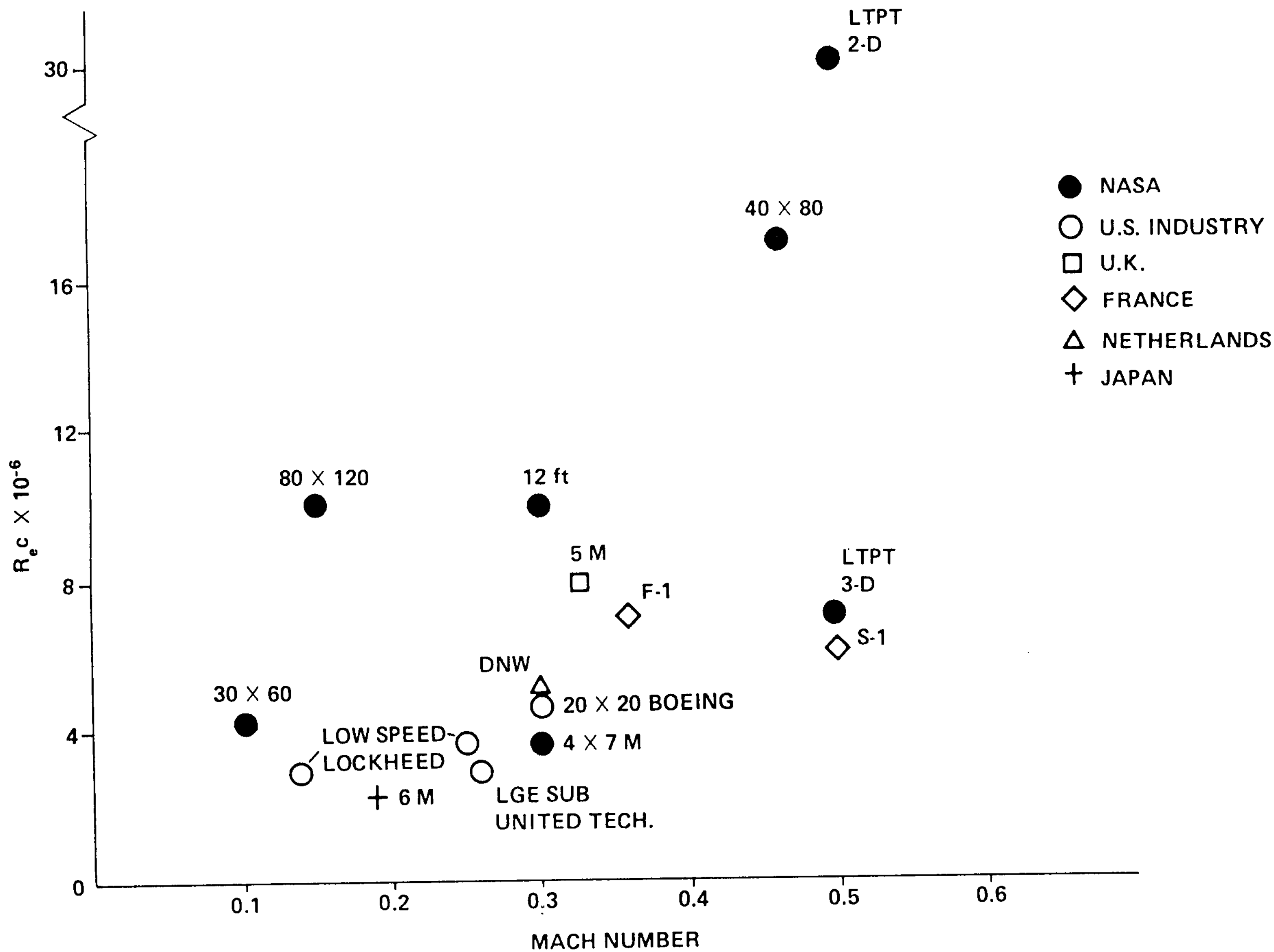


Figure 9. Comparison of major subsonic wind tunnels.

1.3 TRANSONIC WIND TUNNELS

Unlike subsonic tunnels, the population of transonic facilities covers a much narrower range of size and, of course, speed since the primary focus of the latter is in the transonic region (M=0.8-1.2). On the low side, size is limited to tunnels with test sections larger than 4 ft, while on the high side the number of large facilities are limited to the three 16 ft tunnels in the U.S. and the 26 ft S1 tunnel in France. In all, 48 facilities were evaluated, 26 in the U.S. and 22 abroad.

Transonic wind tunnels can be categorized into two major groups: 2-dimensional (2-D) and 3-dimensional (3-D) tunnels. The former are facilities with very narrow (2-dimensional) test sections and involved principally in airfoil research. There are relatively few of these. The latter encompass the majority of the transonic tunnels, and for purposes of this assessment, have been divided into three subgroups based on size:

$3\text{-}D_1$	Larger than 10 ft
$3\text{-}D_2$	7 to 10 ft
$3\text{-}D_3$	Less than 7 ft

The corresponding tunnels are listed in Table IV.

Research and testing in the transonic region is particularly sensitive to good flow quality and high Reynolds number capability. Sufficient size to properly instrument a model and measure the desired parameters is a minimum requirement. This is considered to be at least 4 ft. However, the optimum test section size for transonic tunnels is in the 8 to 11 ft range, which provides adequate size for measurements at reasonable model costs and/or operating costs. This size also can provide high Reynolds numbers under cryogenic conditions, such as with Langley's NTF. The larger size tunnels do provide advantages at near sonic conditions, where wall interference effects are pronounced, by increasing the test section to model size ratio sufficiently to minimize these effects.

TABLE IV

COMPARABLE TRANSONIC TUNNELS

Page Number	Facility Name	Installation
	2-D	
	6 x 28-in	NASA–Langley
	0.3-m TCT (2-D Insert)	NASA–Langley
	High Reynolds Number Tunnel	NASA–Marshall
	Compressible Flow Tunnel	Lockheed–Georgia
	1-ft	McDonnell Douglas–California
	NAE 5-ft (2-D)	Canada–NRC
	T-2	France–ONERA, Tolouse
	TWB	Germany–DFVLR Braunschweig
	2-D	Japan–KHI
	RENO	Japan–NAL
	$3\text{-}D_1$ (3-D >10-ft)	
	S1-MA	France–ONERA, Modane
	TDT	NASA–Langley
	16-ft	NASA–Langley
	16T	DOD–AEDC
	14-ft	NASA–Ames
	11-ft	NASA–Ames
	$3\text{-}D_2$ (3-D 7 to 10-ft)	
	Transonic Wind Tunnel	Boeing–Seattle
	7 x 10-ft	DOD–David Taylor
	NTF	NASA–Langley
	8-ft TPT	NASA–Langley
	8-ft	Calspan
	9 x 8-ft TWT	United Kingdom–ARA, Bedford
	8 x 6-ft	United Kingdom–RAE, Farnborough
	7-ft Trisonic	Rockwell

Page Number	Facility Name	Installation
	$3\text{-}D_3$ (3-D <7-ft)	
	Free Jet (6 x 7)	Lockheed–California
	2-m	Japan–NAL
	HST	Netherlands–NLR
	66-in	FluiDyne
	NAE–5 x 5 ft	Canada–NRC
	S2–MA	France–ONERA, Modane
	4T	DOD–AEDC
	4-ft Trisonic	Lockheed–California
	4-ft Trisonic	McDonnell Douglas–El Segundo
	Polysonic (4-ft)	McDonnell Douglas–St. Louis
	High Speed (4-ft)	Vought
	1.2-m	United Kingdom–BA, Warton
	Sigma 4	France–Inst. Aero. Tech., St. Cyr
	S3-CH	France–ONERA, Chalais
	1-m (TWG)	Germany–DFVLR, Göttingen
	S3-MA	France–ONERA, Modane
	27-in	United Kingdom–Brough
	Trisonic Tunnel (TMK)	Germany–DFVLR, Köln
	26-in	Grumman
	24-in	Northrop
	2 x 2	NASA–Ames
	High Speed (HKG)	Germany–DFVLR, Göttingen
	60-cm Trisonic	Japan–Mitsubishi
	0.3-m (Flexible Wall Insert)	NASA–Langley

1.3.1 SIZE

In terms of size, the tunnels grouped under 3-D1 represent the top of the line, and except for France's S-1 (26 ft), these all belong to the U.S. Government (NASA and AEDC). In the mid or "optimum" sized range, the tunnels listed in groups 3-D2 are owned mostly by the U.S. and the only foreign tunnels are owned by the U.K. The smaller tunnels (3-D3) are evenly spread in the U.S. and abroad, with the U.S. tunnels owned principally by industry.

1.3.2 REYNOLDS NUMBER

In this category, the U.S. is the undisputed leader with NASA Langley's NTF. This new, cryogenic facility provides an order of magnitude increase in the Reynolds number capability heretofore generally available (120 vs. $10x10^6$) at an optimum size of 8 ft. The Europeans are entertaining the possibility of building a similar facility through a consortium of nations (France, Netherlands, Germany, and the U.K.). Although a site has been selected (Koln, West Germany), an operational facility is still 5 to 10 years in the future. The next best Reynolds number capability resides in the group of 4 ft trisonic or polysonic tunnels designed by Fluidyne and dispersed throughout the U.S. industry and some foreign countries including India, Korea, and Taiwan. Table V lists the leading high Reynolds number tunnels, and Figure 10 plots the data against size. Overall, the U.S. has the most capacity and flexibility in this area, although the Canadians and Europeans also have good facilities.

1.3.3 FLOW QUALITY

Quantifiable data for comparing this characteristic was not readily available. However, the "good" facilities are generally well known by researchers in this field. The recently modified Langley 8-ft Transonic Pressure Tunnel (TPT) is judged to be the premier facility in this category. Other than this standout, the qualitative data available indicate that there is a wide variation in flow quality throughout the U.S. and foreign facilities, with no clear edge enjoyed by either side. The general inference is that the flow quality in most transonic tunnels is marginal and that further improvements in facility design with subsequent rehabilitation of many existing facilities is needed.

TABLE V

HIGH REYNOLDS NUMBER TRANSONIC TUNNELS

Tunnel	Location	$R_e c \times 10^{-6}$
NTF	NASA–Langley	120
High R_e	NASA–Marshall	53
4-ft Polysonic	McDonnell Douglas–St. Louis	20
1-m (TWG)	Germany – DFVLR, Göttingen	16
4-ft High Speed	Vought	15
NAE 2-D	Canada–NRC	14
0.3-m	NASA–Langley	14
TDT	NASA–Langley	14
7-ft	Rockwell–Los Angeles	13
NAE 3-D	Canada–NRC	12
4-ft Trisonic	Lockheed–California	12
4-ft Trisonic	McDonnell Douglas–El Segundo	12
Compressible Flow	Lockheed–Georgia	11
S-1 MA	France–ONERA, Modane	11
16-ft	DOD–AEDC	10
11-ft	NASA–Ames	10
8-ft	Calspan	10
1.2-m	India–Bangalore	10
4 x 4-ft	United Kingdom–Warton	10
8-ft	United Kingdom–Bedford	9

$R_{e_{max}} = R_e c$ where $c = 1/10 \sqrt{A_{TS}}$

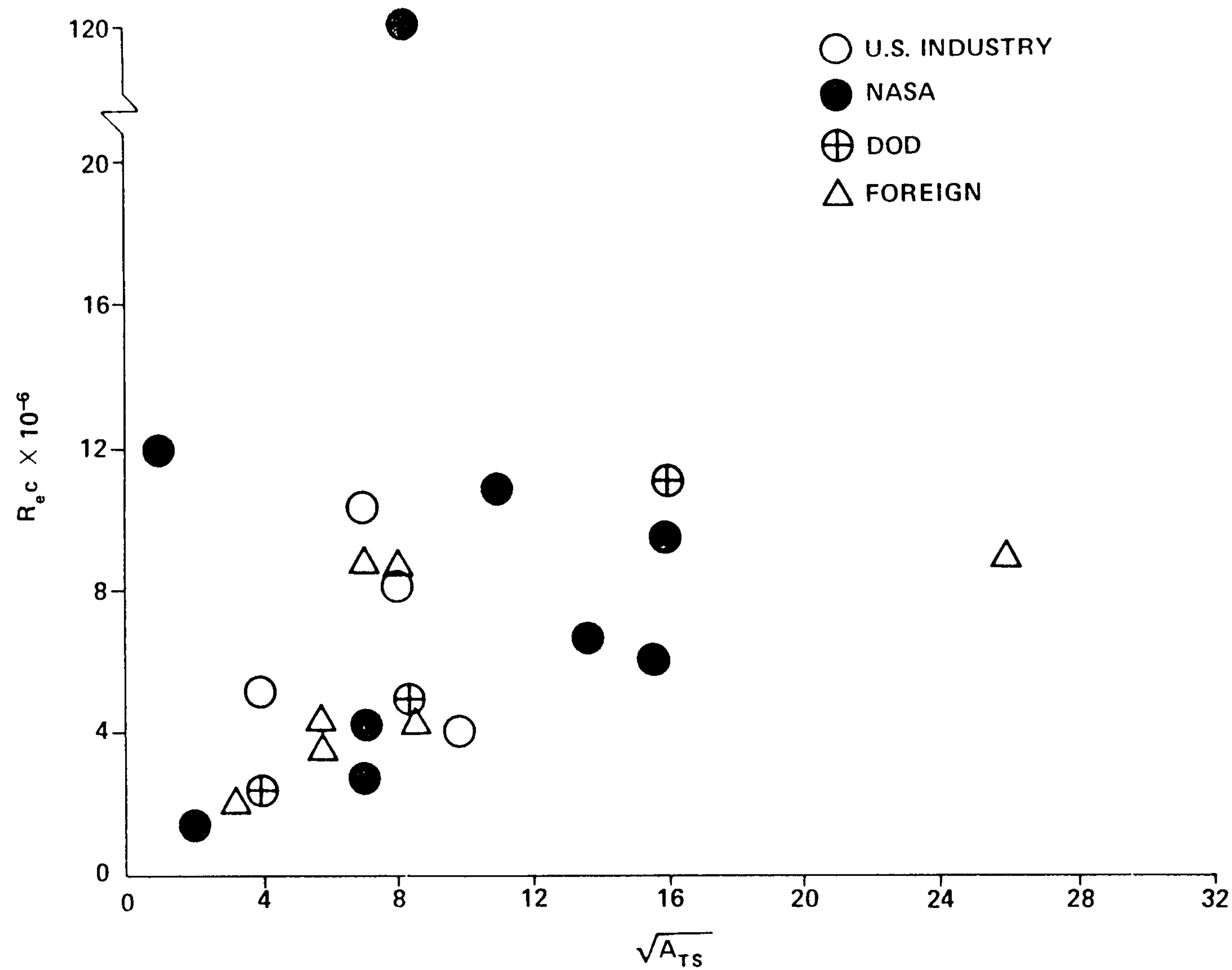


Figure 10. Transonic tunnels.

1.4 SUPERSONIC WIND TUNNELS

About 40 supersonic wind tunnels (including 15 with multiple speed test sections which also are counted as transonics) meeting the set criteria of 2 ft and Mach 1.2- 3.5, or 1 ft and Mach 3.5-5, were examined in this assessment. The population is almost equally divided between the U.S. and foreign, with the U.S. having a slight edge in numbers. Unlike the subsonic and transonic tunnels which were amenable to groupings, the supersonic tunnels were compared on an individual basis to account for the many factors and individual facility characteristics influencing the comparisons in this speed regime.

Overall, the U.S. (NASA and DOD) owns the largest supersonic wind tunnels, with U.S. industry having the highest Reynolds number capability, particularly in their 4-ft polysonic tunnels. Except for size, foreign tunnels are roughly comparable to the U.S., providing maximum Reynolds number capability near the average for this speed regime. This is also a very active set of wind tunnels with considerable backlogs in the more popular facilities, especially the NASA Unitary Plan tunnels. The latter, however, are over 30 years old and are suffering from antiquated technology and low productivity. Specific observations on size, Reynolds number, and flow quality follow.

1.4.1 SIZE

The largest U.S. tunnels are the supersonic propulsion tunnels at AEDC and NASA Lewis (APTU, 16S, 10x10, and 8x6 ft) plus the Unitary Plan Tunnel at Ames (9x7 and 8x7 ft). The largest foreign facility in this category is the U.K.'s 8 ft tunnel, followed by the French S2-MA (~6 ft), and the Canadian NAE 5x5 ft tunnels. Table VI lists the tunnels in this category according to size and comparable capabilities.

TABLE VI

SUPERSONIC TUNNELS

	Facility Name	Installation
	APTU	DOD–AEDC
	16S	DOD–AEDC
	10 x 10-ft	NASA–Lewis
	9 x 7-ft	NASA–Ames
	8-ft	United Kingdom–Bedford
	8 x 7-ft	NASA–Ames
	S2-MA	France–ONERA, Modane
	8 x 6-ft	NASA–Lewis
	7-ft	Rockwell–Los Angeles
	6 x 6-ft	NASA–Ames
	NAE 5 x 5-ft	Canada–National Research Council
	4-ft	India–Bangalore
	4-ft	Lockheed–California
	4-ft-Trisonic	McDonnell Douglas–El Segundo
	Polysonic (4-ft)	McDonnell Douglas–St. Louis
	SST (4-ft)	Netherlands
	4-ft	United Kingdom–Warton
	High Speed (4-ft)	Vought
	S3-MA (Supersonic)	France–ONERA, Modane
	30 x 27-in	United Kingdom–Woodford
	27 x 27-in	United Kingdom–Brough
	24-in	Northrop
	Trisonic (TMK)	Germany–DFVLR
	2 x 2-ft	Japan–Fuji Heavy Industries

*In order of appearance.

	Facility Name	Installation
	60-cm	Japan–Mitsubishi
	Supersonic #2	DOD–NSWC
	4-ft	Boeing–Seattle
	1-m	Japan–National Aerospace Laboratory
	High Speed (HMK)	Germany–DFVLR
	Unitary Tunnel	NASA–Langley
	3 x 4-ft	United Kingdom–Bedford
	von Karman A	DOD–AEDC
	SWT	United Kingdom–Bedford
	C-4	France–L.R.B.A. French Army
	15-in	Grumman
	1 x 1-ft	NASA–Lewis
	Boundary Layer	DOD–NSWC
	Mach 3 High Reynolds Number	DOD–WAL
	Ludwieg Tube	Calspan

1.4.2 REYNOLDS NUMBER

The best Reynolds number capability in this speed regime is available in the group of 4 ft polysonic tunnels owned mostly by the U.S. industry and some foreign countries such as the Netherlands, the U.K., and India. Table VII identifies those tunnels with the highest $R_{e_{max}}$, and Figure 11 plots this value as a function of test section size. This graph illustrates that although NASA and DOD facilities are the largest, the U.S. industry and some foreign facilities provide much higher Reynolds numbers.

1.4.3 FLOW QUALITY

The elements affecting flow quality in the high-speed tunnels are inherently different from the low speed ones. The latter are influenced by fan noise and turbulence occurring upstream of the test section nozzle. The former are affected principally by the turbulence noise generated from the nozzle wall boundary layer, which for the more conventional type of supersonic tests involving mostly force and pressure measurements on relatively simple aerodynamic shapes, can be ignored altogether. Moreover, the Mach number variations across a test section are usually well mapped and appropriate corrections are available for test results so as to compensate for these irregularities. For these reasons, flow noise characteristics of supersonic tunnels have generally not been well determined nor documented, and there's little data available for significant comparisons.

Overall, most of the supersonic tunnels surveyed offer adequate flow characteristics for conducting the more traditional type of research and testing. No premier facility stands out, not even NASA's Unitary Plan Wind Tunnels. However, as interest in the more complex aerodynamic shapes of future vehicles increases, the effects of flow noise on boundary layer thickness and laminar flow transition will be critical. Quiet, low disturbance supersonic tunnels will be a necessity. At this time, no such tunnels exist anywhere except for a small pilot facility at Langley.

TABLE VII

HIGH REYNOLDS NUMBER SUPERSONIC TUNNELS

Tunnel	Location	$R_e c \times 10^{-6}$
4-ft Polysonic	McDonnell Douglas	200
4-ft High Speed	Vought	150
7-ft	Rockwell–California	130
NAE 3-D	Canada–NRC	120
4-ft Trisonic	McDonnell Douglas–El Segundo	120
4-ft Trisonic	Lockheed–Georgia	120
4-ft SST	Netherlands	120
4-ft	India–Bangalore	100
4-ft	United Kingdom	95
Ludwieg Tube	Calspan	80
15-in	Grumman	75
Mach 3	DOD–WAL	70
4-ft	Boeing–Seattle	70

$c = \sqrt{A_{TS}}$

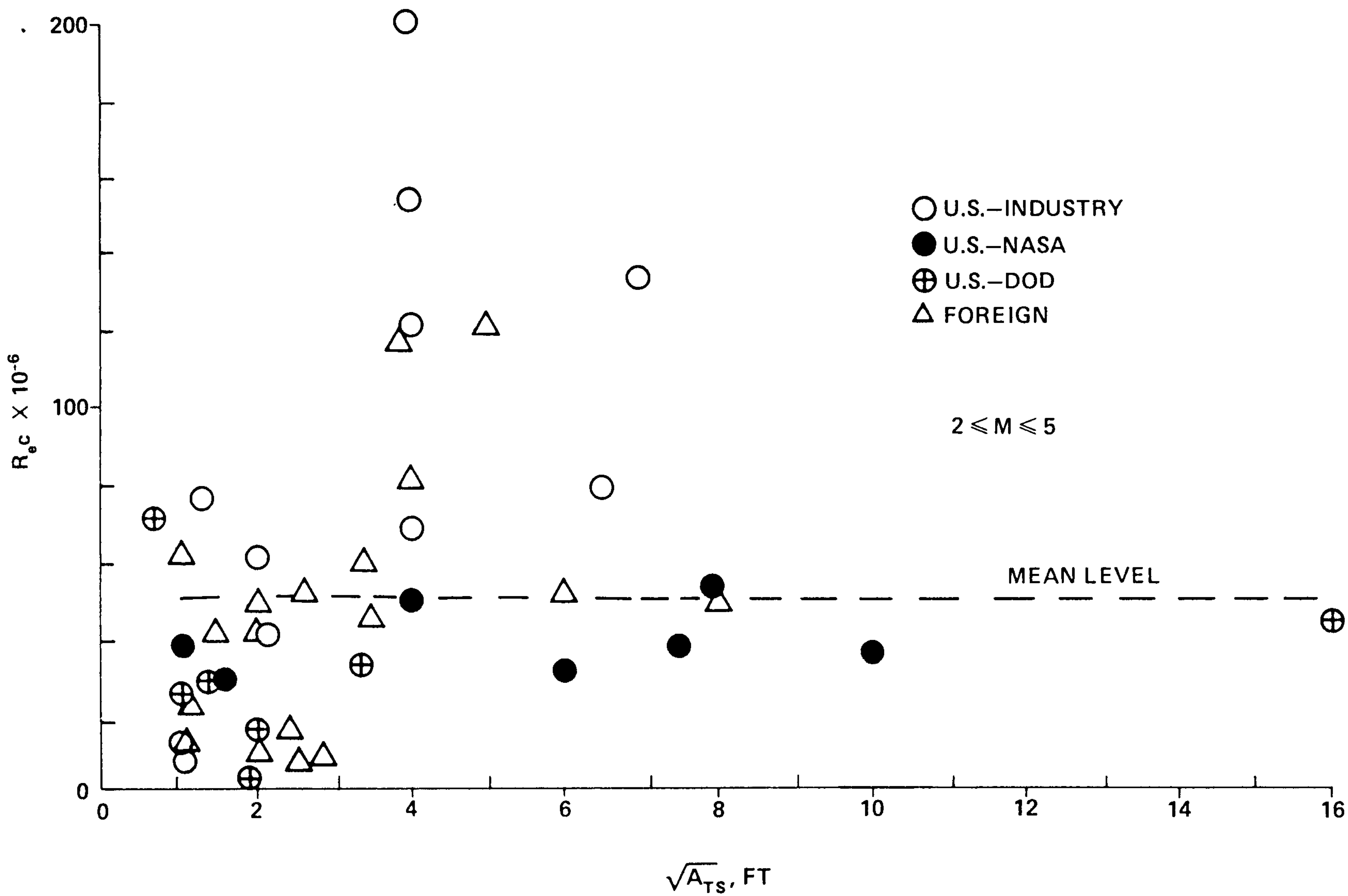


Figure 11. Supersonic tunnels.

1.5 HYPERSONIC WIND TUNNELS

The tunnels covered under this category are those providing speeds greater than Mach 5 and test section sizes of at least 12 inches. Thirty-nine tunnels met this criteria and were compared in this assessment. Of the four wind tunnel categories, the hypersonics are probably the most unique and varied in design and capabilities, and therefore in application. There are two principal types of tunnels: the continuous flow or relatively long duration blow-down tunnels, and the "impulse" or very short duration tunnels (shock tunnels, Ludwig-tubes, etc.). The first group provides runs that are either "continuous" or in the 10 to 100 second range. The impulse tunnels, on the other hand, provide run times on the order of tenths or thousands of a second. Most of the tunnels covered in this assessment, however, fall in the first category since the impulse tunnels are either too small to fit the set criteria, or are no longer operational.

Because of the wide range of flow conditions encountered in hypersonic flight, it is extremely difficult to simulate them all in any single facility. Mach number, Reynolds number, temperature, and pressure are critical parameters that must be properly simulated in the laboratory to represent true flight conditions. Unfortunately, some of these parameters, such as temperature and Reynolds number play against each other making the simultaneous creation of a high temperature, high Reynolds and Mach number environment an almost impossible demand of any single ground-based facility; at least of the ones currently available. For this reason, hypersonic facilities have been designed to cover some specific aspect of this flight regime, such that Mach and Reynolds numbers are duplicated as realistically as possible in one type of tunnel; heat loads are studied in specialty tunnels equipped with arc jet heaters; and real gas effects in high enthalpy facilities. Consequently, except for being generally labeled under one of the two basic categories defined above, this assessment considered each hypersonic facility individually in making comparisons.

Overall, the U.S. has a clear advantage in this speed regime. Good facilities exist in industry and in government laboratories, with the premier, active facilities being at AEDC, NASA Langley, and Calspan. Langley has the distinction of owning a hypersonic complex that offers the full range of tailored capabilities discussed above. Taken individually, these facilities may not each be the best in their class, but as a complex, their combined capabilities are unmatched in the free world. Langley also has the premier high temperature structures hypersonic tunnel in its 8 ft HTT. This tunnel is currently being modified to also serve as a SCRAM jet propulsion facility.

Other comparisons made by size, Reynolds number, and Mach number capabilities follow.

1.5.1 SIZE

The U.S. is the undisputed leader in wind tunnel size with Langley's 8 ft High Temperature Tunnel (HTT) and 5 ft Mach 20, High Reynolds Helium tunnel; Calspan's 96 inch and 48 inch shock tunnels; and the Naval Surface Weapons Center's Hypersonic #8a and #9 tunnels. Nothing comparable exists in the rest of the free world. Table VIII lists the hypersonic tunnels according to size and comparable capabilities.

1.5.2 MACH NUMBER

The largest Mach number range is also in the U.S. tunnels, evenly distributed throughout NASA, DOD, and industry. France's C-2 tunnel is the only comparable foreign facility.

1.5.3 REYNOLDS NUMBER

A comparison of those tunnels having the greatest Reynolds number (Re_{max}) capability is given in Table IX and Figure 12. The U.S. tunnels are also

TABLE VIII

HYPERSONIC TUNNELS

	Facility Name	Installation
	8-ft HTT	NASA–Langley
	96-in Shock Tunnel	Calspan
	48-in Shock Tunnel	Calspan
	Hypervelocity #9	DOD–NSWC
	Hypervelocity #8A	DOD–NSWC
	Mach 20 High Reynolds Number He	NASA–Langley
	Hypersonic Helium	NASA–Langley
	von Karman B	DOD–AEDC
	von Karman C	DOD–AEDC
	Continuous Flow	NASA–Langley
	C-2	France–L.R.B.A. French Army
	3.5-ft	NASA–Ames
	36-in	Grumman
	30-in	Lockheed–California
	30-in	Northrop
	H2K	Germany–DFVLR
	2-ft	McDonnell Douglas–El Segundo
	S4-MA	France–ONERA, Modane
	20-in Mach 6	NASA–Langley
	CF_4	NASA–Langley
	20-in	FluiDyne
	20-in	DOD–WAL

*In order of appearance.

	Facility Name	Installation
	Mach 8 Variable Density	NASA–Langley
	Hypersonic #8	DOD–NSWC
	Guided Weapons Tunnel	United Kingdom–Warton
	18-in	Sandia Laboratories
	Hypersonic Nitrogen	NASA–Langley
	Mach 6 High Reynolds Number	NASA–Langley
	Mach 6 High Reynolds Number	DOD–WAL
	R3-CH	France–ONERA, Chalais-Meudon
	R2-CH	France–ONERA, Chalais-Meudon
	M7T	United Kingdom–Bedford
	M4T	United Kingdom–Bedford
	Scramjet	NASA–Langley
	High Temperature Storage Heater	General Applied Science
	VAH	General Applied Science
	HPB	General Applied Science

TABLE IX

HIGH REYNOLDS NUMBER HYPERSONIC TUNNELS

Tunnel	Location	$R_e c \times 10^{-6}$
96-in shock	Calspan	139
48-in shock	Calspan	92
Hypervelocity #9	DOD–NSWC	92
Hypersonic #8	DOD–NSWC	85
Mach 20 He	NASA–Langley	69
Mach 6 high R_e	NASA–Langley	45
Mach 6 high R_e	DOD–WAL	28
3.5-ft	NASA–Ames	24

$$c = \sqrt{A_{TS}}$$

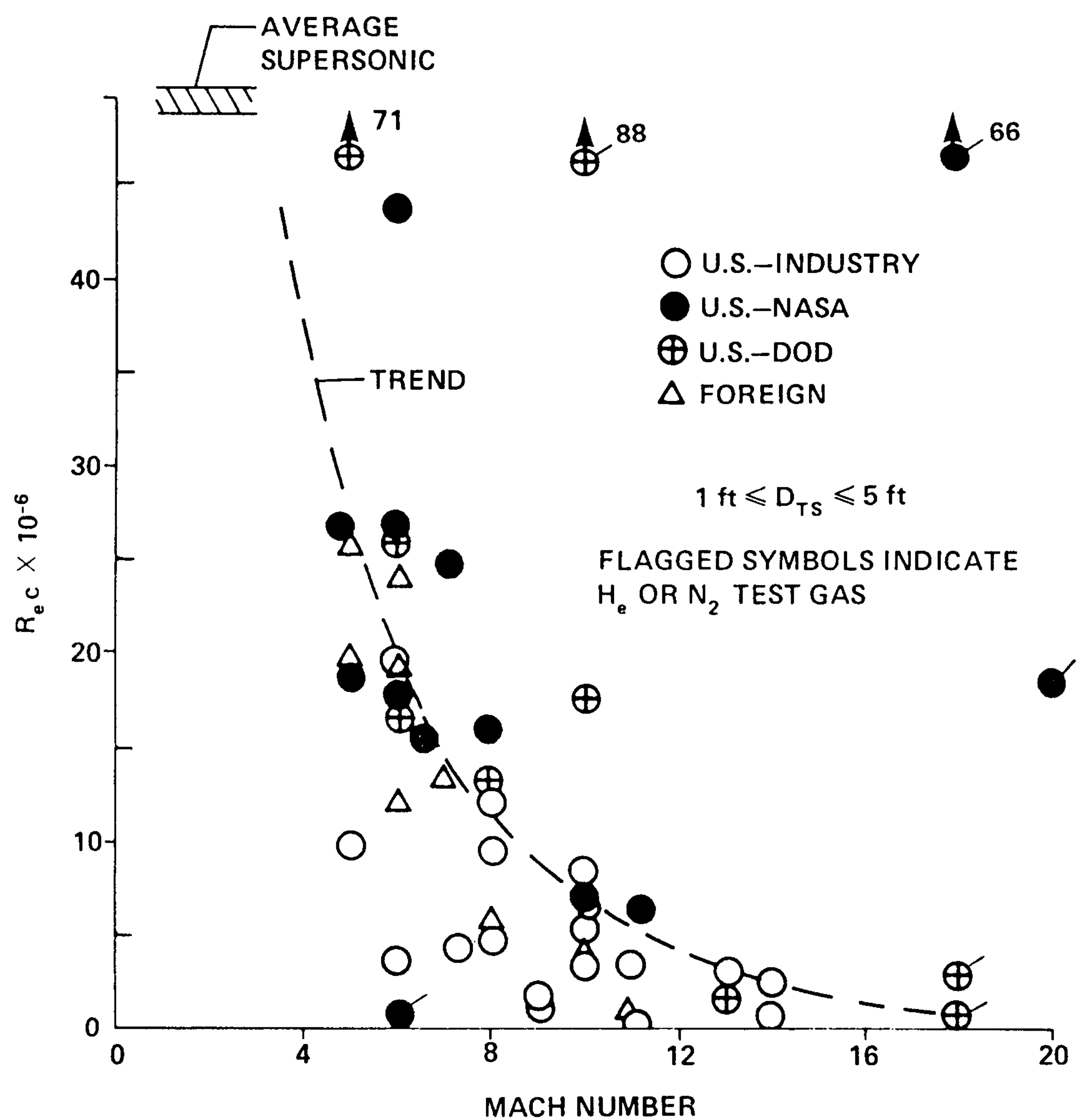


Figure 12. Hypersonic tunnels.

the leaders in this capability with the Calspan 96 in. and 48 in. Shocktunnels out front, followed by DOD and NASA tunnels. The closest foreign tunnels are the U.K.'s M4T and M7T in Bedford.

A summary observation is that this area of research has been sorely neglected in recent years, with a consequential effect on the health of its facilities. Many have been placed on standby status or dismantled. This is particularly evident in the U.S. industry. Of the 50 U.S. facilities listed in the 1979 AEDC survey which would have otherwise met our present criteria, only about 30 are still operational and included in the current catalogue. As mentioned previously, the population of impulse tunnels, where much of the basic research is conducted, has been especially affected.

Of the hypersonic facilities that are still operational, most are very old and in serious need of rehabilitation, especially the Langley complex. Furthermore, the existing range of capabilities is inadequate to meet most of the demands anticipated by the class of hypersonic vehicles envisioned for the year 2000. Specifically, larger, high-thermal, high Reynolds and Mach number facilities will be needed to cover the flight conditions to be experienced by these vehicles and to permit large scale testing of complex aerodynamic/propulsion configurations and the corresponding aerothermal effects.

Last, but probably most important, is the serious lack of experienced, knowledgeable personnel to operate and conduct research in these facilities. Obviously, one is no good without the other. This comment applies equally to foreign capabilities as well as to those in the U.S.

1.6 NASA'S POSITION IN WIND TUNNELS

NASA owns several premier wind tunnel facilities in each of the speed regimes, providing large size, good flow characteristics, high Reynolds number capabilities, and a substantial range of Mach numbers. Most prominent are:

Subsonic Tunnels:

ARC - 40x80x120 ft. complex
- 12 ft. Pressure Tunnel

LRC - 30x60 Full Scale Tunnel
- 4x7 meter
- Low Turbulence Pressure Tunnel (LTPT)

LeRC - Icing Research Tunnel (IRT)

Transonic Tunnels:

ARC - 11 ft. Unitary Plan Tunnel

LRC - NTF
- 8 ft. Transonic Pressure Tunnel (TPT)
- Transonic Dynamics Tunnel (TDT)
- 16 ft.

Supersonic Tunnels:

ARC - 9x7 & 8x7 Unitary Plan Tunnels

LeRC - 10x10 Propulsion Tunnel
- 8x6 Propulsion Tunnel

Hypersonic Tunnels:

ARC - 3-5 ft.

LRC - 8 ft. High Temperature Tunnel (HTT)
- Hypersonic Complex

These represent key assets in the Nation's overall supremacy in this category of aeronautical facilities. However, as discussed in Section 4, this large capital investment is about 30 years old (average) and needs to be protected against further aging and obsolescence through well planned maintenance and rehabilitation/modernization programs. Otherwise, NASA's inventory of wind tunnels appears adequate to meet most of the foreseeable needs, except for those specific requirements addressed in this report (e.g., hypersonics, propulsion-airframe integration, and low disturbance supersonic research facilities).

2. AIRBREATHING PROPULSION FACILITIES

2.0 INTRODUCTION

The airbreathing propulsion facilities covered by this assessment fall into three categories:

- Propulsion Wind Tunnels
- Altitude Engine Test Facilities
- Engine/Propulsion Component Facilities

These three categories cover the full range of facilities required to develop and improve the aircraft engines used by both civil and military aviation.

The wind tunnels included in this section are only those that permit real engine testing (engine burn) while the wind tunnel is in operation. Tunnels that provide only propulsion simulation capabilities through the use of compressed air driven engine simulators (or similar techniques) are not included in this comparison. They are covered with the other tunnels in the Wind Tunnel section. The engine test facilities covered in this assessment are only those providing altitude test capability. Sea level test stands are too numerous and do not provide the proper temperature and pressure conditions required in conducting full range engine research and development. Engine test facilities with both direct connect and free jet capabilities are included. Of the engine/propulsion component facilities, only those providing R&D or testing capabilities for turbines, compressors, fans, and combustors have been included. Other facilities, rigs, or equipment dealing with fuels, lubricants, bearings, seals, and materials were considered too numerous and widespread for this survey. Additionally, the latter generally represent much smaller facilities requiring low capital investments, and therefore are much more abundant throughout the aeropropulsion industry, government laboratories, and academia.

This survey covered U.S. Government laboratories, industry and foreign installations. The response was good from the U.S. sources but only marginal to poor from other countries; particularly for component facilities where the response was negligible. Nevertheless, the Assessment Team worked with the data submitted plus their own personal knowledge to arrive at the opinions expressed herein. Refer to Table I-b for the distribution by country/owner.

2.1 SUMMARY ASSESSMENT

Overall, the U.S. owns the largest number and most capable propulsion facilities in the free world, with industry and government laboratories sharing this wealth almost equally. The U.S. laboratories (NASA and DOD's AEDC) own the best propulsion tunnels; industry and AEDC offer the best engine test capabilities; and industry has the most modern and comprehensive set of propulsion component facilities. The best foreign airbreathing propulsion capabilities are the engine test facilities in the U.K. (Peystock) and in France (Saclay). NASA's strongest suit is in its propulsion wind tunnels and in its overall propulsion research capabilities, which combine its facilities and research staff. Due to its low air flow capacity, NASA does not own any premier engine test facilities, but it does own (or is in the process of obtaining) some unique research capabilities in the components area.

2.2 PROPULSION WIND TUNNELS

Propulsion testing in wind tunnels allows the engine and its installed inlet to be tested as an integrated system. The propulsion system is presented with an air flow environment similar to that encountered in real flight where the air is directed around the inlet as well as into it. Other elements of the propulsion system or aircraft are likewise exposed to the same environment and are free to interact with one another as in actual flight conditions. In the larger wind tunnels the angle of attack can also be varied, resulting in even more realistic air flow

TABLE X

PROPULSION WIND TUNNELS

Facility/Cell Designation	Mach No.	Pressure (PSIA)	Altitude (Feet)	Temp. (^oF)	Size (Feet)	Maximum Thrust (lbf)	Remarks
10x10 SWT, NASA, LeRC	2.0 - 3.5	1.4 35	77,000	60 690	10x10x40L	20,000	Single Pass
8x6 SWT, NASA, LeRC	0.36 - 2.0	1.4 8.5	---	60 266	8x6x39L	5,000	Single Pass
16T, AEDC	0.06 - 1.6	3.0 26.3	90,000	80 160	16x16x40L		Exhaust Scoop
16S, AEDC	1.5 - 4.75	3.0 12.5	150,000	120 620	16x16x40L		Exhaust Scoop
S1-MA, ONERA	0.023- 1.0	.9 Atmos	20,000	5 122	20.5x22x46L or 26D		20% Air Exchange
DNW, Netherlands	0 - 0.4 0 - 0.3 0 - 0.18	Atmos	---	Ambient	26.5 x 20 31x31 20x20		Air Exchange
40x80, NASA, ARC	0 - 0.4	1 Atmos	---	Ambient	40x80x80L		Air Exchange
80x120, NASA, ARC	0 - 0.15	1 Atmos	---	Ambient	80x120x190L		Single Pass
9x9 PWT, Boeing	0 - 0.33	1 Atmos	---	Ambient	9x9x14.5L		Single Pass
10x20 NRC, Canada	0.007- 0.184	1 Atmos	---	Ambient	10x20x40L		Single Pass

conditions for the engines. For complete aerodynamic behavior and propulsion/airframe integration studies, the wind tunnel is not surpassed. The deficiency of wind tunnels for engine testing is their inability to obtain true temperature simulation over a wide operating range. In general, the air in a wind tunnel is not hot enough at the high Mach numbers nor cold enough at the high altitudes and lower Mach numbers. Moreover, conditioning the large volume of air used by the tunnel in addition to that used by the engine itself is a difficult, costly, and inefficient process. Engine test facilities are more economical in this respect for low bypass engines and generally have better provisions for temperature/altitude simulation.

There are very few true propulsion tunnels in the free world (see Table X). This table indicates that the majority are in the U.S. at either NASA or the DOD. The NASA capabilities include the large low speed 40x80x120 tunnel at Ames plus the 10x10 and 8x6 ft supersonic tunnels at Lewis. The DOD owns the premier transonic and supersonic facilities at AEDC with their pair of 16 ft tunnels. In the Hypersonic regime, NASA will own the only large facility when the 8 ft High Temperature Tunnel is modified with oxygen enrichment in 1986. The European capability is all low speed and is located in France (S-1 MA) and the Netherlands (DNW). The U.S. industry has a 9x9 ft low speed facility owned by Boeing and a few small hypersonic tunnels owned by General Applied Sciences. The U.S. is clearly the leader in this category.

However, at the present time there are no facilities in the free world that can provide the proper altitude and temperature controlled environment in which to conduct large scale, true propulsion/airframe integration research. NASA is attempting to fill this gap with their proposed Altitude Wind Tunnel facility project at LeRC.

2.3 ALTITUDE ENGINE TEST FACILITIES

Propulsion testing in Altitude Engine Test Facilities falls into two broad categories: direct connect and free jet testing. In the direct connect version, air is fed directly into the engine, eliminating (or bypassing) the use of an inlet and avoiding any loss of air flowing around the engine. The intent is to present properly conditioned combustion air to the engine as if an inlet were present but in a more efficient manner. Usually this air is presented in an idealized, uniform profile, although provisions are often available for introducing temperature and pressure profile distortions. The smaller, more easily controlled volume of air is thereby easier to condition for the temperature extremes (hot or cold) required for true simulation of engine operation at high Mach numbers, or at high altitude and low Mach number. Not all facilities, however, offer all of the desired conditions, either because they were designed for specific applications or certain limitations were imposed due to cost or the technology available at the time of construction.

In free jet engine test stands, the engine and its inlet are mounted so the air from a nozzle can impinge on the engine's inlet. This configuration is similar to a wind tunnel except that the quality of the air flow is seldom as good. However, free jet facilities are still more economical since the air can be directed right at the inlet, and the provisions for good temperature simulation are also available. The angle of attack capabilities are generally very limited but they can be extended in the larger facilities. Generally, a free jet capability is available as an option or specific configuration of a direct connect facility.

Of the more than 80 Engine Test facilities examined, about 60 offered altitude simulation capability and were compared in this assessment. Of these, 42 belong to the U.S. with a replacement value of more than $2.5 billion, most of it invested in the DOD facilities at AEDC.

In order to perform a meaningful comparison of these facilities, they were categorized into three airflow/Mach number groups, each suitable for testing a particular class of engines. A fourth group of those facilities offering free jet capabilities was also compiled and compared.

GROUP 1: Facilities capable of testing large high bypass turbofan engines at an air flow of 1200 lb/sec or greater and air speeds less than Mach 1.

GROUP 2: Facilities appropriate for testing large turbojet, small high bypass turbofan, and low bypass turbofan engines with an air flow of 480 lb/sec or larger and air speeds of Mach 3.0 or greater.

GROUP 3: Facilities for testing medium and/or small turbojet engines, with an air flow of less than 480 lb/sec and air speeds up to Mach 3.5.

GROUP 4: Facilities offering a free-jet testing capability.

Tables XI-a-d list individual facilities in each of the above groups. Because free-jet testing may be an additional rather than a sole capability at some facilities, Group 4 contains some facilities that are also listed in the other groups.

2.3.1 HIGH FLOW, HIGH BYPASS, LOW SPEED TURBOFANS (GROUP 1)

Table XI-a lists those facilities capable of testing these large engines. The premier capability in this category resides in the U.S. at DOD's AEDC. Of the seven test chambers listed, the four with the highest flow are at AEDC. Two of these, ASTF-C1 and C2, are brand new modern chambers currently being checked out for operations (summer of 1985). The ASTF complex will have full transient test capability, providing for the simultaneous programming of engine speed, Mach number, and altitude conditions. Both refrigerated and hot air conditioning are available, with the latter being necessary in testing at high Mach numbers; a capability that makes the AEDC facilities more flexible than all the other test facilities in this category.

Following AEDC, the next best capability based on air flow is in the U.K. at the RAE-Pyestock facilities in Farnborough. Test cell 3W has an air flow capacity of 1390 lb/sec, a very respectable capability in this category. American industry also has some good capabilities in this category at the Pratt & Whitney Willgoos Laboratories' test cells X217 and X218. These facilities can deliver an air flow of 1200 lb/sec, with test cell X218 also providing transient testing capabilities. The next largest American commercial facility is the General Electric (Cincinnati) test cells #43 and 44 with a capacity of 1000 lb/sec, which, although not meeting the 1200 lb/sec criteria, are used extensively for testing large turbofan military engines.

NASA does not have any capability in this category, and probably will not since the field is well covered by DOD and industry. Furthermore, indications are that the direction of future research is toward high performance supersonic engines rather than larger subsonic transport engines.

2.3.2 LARGE TURBOJET, SMALL HIGH BYPASS AND LOW BYPASS TURBOFAN Engines (Group 2)

Table XI-b lists those facilities capable of testing these medium flow, high-speed engines (≥480 lb/sec, M≥3). Again, the premier capability in the Western World is at AEDC with its ETF-T1, T2, T4, J1 and J2, in addition to their ASTF complex. All provide large flows of heated and refrigerated air offering good simulation of engine conditions over a wide operating range. The lead position of the U.S. is further strengthened by substantial capabilities at other U.S. Government agencies (NAPC and NASA - Lewis) and U.S. industry (P & W and G.E.). Outside the U.S., France (CEPr) has very good capability at the high flows over a wide Mach number range. The U.K. has reasonable air flow/Mach number capability with the added advantage of transient testing abilities.

Even though this is the area where the bulk of future engine research is anticipated, NASA's capability in this category of facilities is limited due to low air flow and exhaust capacity. From a development standpoint, one facility with the overall capability of AEDC's ASTF is all that is needed by the U.S.. However, from a research perspective, the NASA Lewis facilities would need upgrading to increase their current flow capacity and provide full transient test capability if the full spectrum conditions for these types of engines are to be simulated and investigated.

2.3.3 MEDIUM AND/OR SMALL TURBOJET ENGINES (Group 3)

As illustrated in Table XI-c, the test facilities in this category are evenly distributed throughout the Western World in both industry and government agencies, with the U.S. neither in the lead nor at a disadvantage. NASA has no comparable facility dedicated specifically in this range, although the Lewis PSL #3+4 test cells have the capability to test this category of engines.

2.3.4 FREE-JET CAPABILITIES (Group 4)

Table XI-d lists the Free-Jet test facilities/capabilities surveyed for this assessment. Many of these represent an additional capability to test facilities already listed under the previous categories, but are repeated with the dedicated free-jet facilities for purposes of completeness. With the addition of a free-jet capability at AEDC's ASTF-C2 in 1987, the U.S. will have the free world's premier facility for this type of engine testing. This lead position is further strengthened by the excellent facilities at the Marquardt Company in Van Nuys, California. The European capability is evenly distributed between the British (7) and the French (5), but is not comparable to that of the U.S.. NASA, on the other hand, relies on its large propulsion wind tunnels to conduct similar type engine testing.

2.3.5 SUMMARY

The most important parameters in comparing Altitude Engine Test Facilities are their air handling capacities (both supply and exhaust) and their ability to supply both hot and refrigerated air. Providing full transient test capabilities is another distinguishing characteristic of the World Class facilities. Figure 13 compares the NASA - Lewis capabilities with those of AEDC's ASTF, U.K.'s RAE (Pyestock), and France's CEPr in Saclay. The air supply and exhaust pressures are plotted against air flow showing clear evidence that the outstanding overall capability is at AEDC, with its ability to provide high flows at high pressures, matched by the appropriate exhaust capacity. The air handling capability of the U.K.'s RAE (Pyestock) is also very impressive but falls short of AEDC's exhaust capacity at high flows. The NASA Lewis exhaust capabilities are similar to those of France's CEPr, while their relative air supply capacities vary depending on the operating pressure levels.

Figure 14 shows a histogram comparing air handling capacities for various facilities/installations. This comparison also indicates that the U.S. (AEDC) is the leader in this category, followed by the U.K.

TABLE XIa

ALTITUDE ENGINE TEST FACILITIES *

SUITABLE FOR TESTING LARGE BYPASS TURBOFAN ENGINES

(Air Flow $\geq$ 1200 #/sec, Capability of Testing at M < 1)

Facility/Cell Designation	Air Supply			Mach No.	Altitude (Feet)	Physical Size (Feet)	Thrust Stand (lbf)	Remarks
	Flow (PPS)	Temp (°F)	Pressure (PSIA)					
AEDC, ASTF-C2	2760	-100 +650	Atmos	3.0	100,000	28D x 85L	75,000	Transient Testing
AEDC, ASTF-C1	1460	-100 +1020	40	3.8	100,000	28D x 85L	75,000	Transient Testing
AEDC, ETF-J2	1400	-10 +750	35	3.2	80,000	20D x 103L	70,000	
AEDC, ETF-J1	1400	-15 +750	13	3.2	80,000	16D x 72L	50,000	
RAE (PYE), 3W	1390	-35 Ambient	Atmos	1.0	59,000	25D x 56L	50,000	Icing
P&W-AW, X218	1200	-10 +90	12.5	1.0	40,000	24D x 45L	100,000	Transient Testing
P&W-AW, X217	1200	-10 +90	12.5	1.0	40,000	18D x 35L	50,000	

* Tables indicate limits of capabilities only

TABLE XIb

ALTITUDE ENGINE TEST FACILITIES

SUITABLE FOR TESTING LARGE TURBOJET; SMALL, HIGH BYPASS

TURBOFANS; AND LOW BYPASS TURBOFANS

(Minimum Air Flow $\geqslant$ 480 lb/sec, Capability of Testing to at Least M = 3)

Facility/Cell Designation	Air Supply Flow (PPS)	Air Supply Temp (^{o}F)	Air Supply Pressure (PSIA)	Altitude (Feet)	Mach No.	Physical Size (Feet)	Thrust Measurement (lbf)	Full Transient Capability
AEDC, C-2	1460	-100 +650	50	100,000	3.0	28D x 85L	75,000	Yes
AEDC, C-1	1460	-100 +1020	40	100,000	3.8	28D x 85L	75,000	Yes
AEDC, J-2	1400	-10 +750	35	80,000	3.2	20D x 103L	70,000	No
GE, TC-43*	1000	AMB +650	43	60,000	1-3.0	12D x 56L	Yes	No
GE, TC-44*	1000	AMB +650	43	60,000	1-3.0	17D x 56L	Yes	No
GE, TC-45*	1000	AMB +650	43	60,000	1-3.0	17D x 56L	Yes	No
CEPr, R-5	825	(Refig.) +1200	100	66,000	4.0	18D x 100L	67,000	No

*Minimum subsonic test capability (no refrigerated air)

TABLE XIb (Continued)

Facility/Cell Designation	Air Supply Flow (PPS)	Air Supply Temp (°F)	Air Supply Pressure (PSIA)	Altitude (Feet)	Mach No.	Physical Size (Feet)	Thrust Measurement (lbf)	Full Transient Capability
AEDC, T-1	800	-120 +650	35	80,000	3.0	12.3D x 75L	30,000	No
AEDC, T-2	800	-120 +650	35	80,000	3.0	12.3D x 68L	30,000	No
AEDC, T-4	800	-120 +650	35	80,000	3.0	12.3D x 55L	30,000	No
AEDC, J-1	700	-65 +750	40	80,000	3.2	16D x 72L	50,000	No
NAPC, 3E	700	-65 +650	30	80,000	3.0	17D x 30L	50,000	No
RAE, (PYE) ATF-3	600	-100 +872	29	62,000	3.5	20D x 80L	50,000	Yes
P&WA, X-208	580	-20 +625	45	80,000	3.0	12D x 34L	25,000	No
NASA LeRC, PSL-3	480	-50 +600	60	80,000	3.0	24D x 38L	40,000	No
NASA LeRC, PSL-4	480	-50 +1200	60	80,000	4.0	24D x 38L	40,000	No

TABLE XIc

ALTITUDE ENGINE TEST FACILITIES

SUITABLE FOR TESTING MEDIUM OR SMALL TURBOJET ENGINES

(Air Flow $<$ 480 #/sec, M $\leqslant$ 3.5)

Facility/Cell Designation	Air Supply Flow (PPS)	Air Supply Temp (°F)	Air Supply Pressure (PSIA)	Mach No.	Altitude (Feet)	Physical Size (Feet)	Thrust Stand (lbf)	Remarks
GE, TC-40	450	-100 +400	60	2.5	600	20 x 20 x 60L		
CEPr, R-3	441	-85 +390	30	2.4	65,000	11.5D x 60L	45,000	
CEPr, R-4	441	-85 +390	30	2.4	65,600	11.5D x 60L	45,000	
NAPC, 1E	430	-65 +320	30	3.0	80,000	14D x 18L		Icing
NAPC, 2E	430	-65 +320	30	3.0	80,000	14D x 18L		Icing
Allison, 881	420	-40 +210	26.5	1.0	50,000	18D x 65L	30,000	
RR (DE), ATF-1	400	-113 +355	73	2.5	70,000	9D x 38L	20,200	
RR (DE), ATF-2	400	-113 +355	73	2.5	70,000	9D x 38L	20,200	
AEDC, ETF-T6	375	-30 +300	70	3.0	90,000	3D x 18L		Plume Studies
CEPr, S1	221	-- +661	29	3.5	62,000	20D x 80L	50,000	Icing

TABLE XIc (Continued)

Facility/Cell Designation	Air Supply Flow (PPS)	Temp (^{o}F)	Pressure (PSIA)	Mach No.	Altitude (Feet)	Physical Size (Feet)	Thrust Stand (lbf)	Remarks
P&W, 209	200	-20 +650	12.5	3.0	80,000	12D x 34L	25,000	
GE, TC-A1	175	-70 +100	100	2.5	85,000	7 x 8 x 16.5L		
US-ILA, HPT	154	-100 +350	28	2.2	65,600	10D x 33L	22,500	
CEPr, C1	121	-86 +175	17	1.0	36,000	11D x 26L	2,250	
Allison, 871	120	-75 +160	30	1.7	50,000			Turboshaft 15,000 HA
Allison, 872	120	-75 +160	30	1.7	50,000			Turboshaft 8000 HA
Allison, 873	120	-75 +160	80	1.7	45,000	14D x 40L		Turboshaft 10,000 HA
AEDC, ETF-T5	50	-65 +650	40	3.0	80,000	7D x 17L	5,000	
NRC, Alt. Tst. Ch.	12	-70 +212	160	0.7	45,000	7D x 12L		
Mitsubishi, 1007	12	-50 +180	33	1.2	20,000	8D x 40L		
Allison, 885	10	-75 +160	30	1.0	25,000			Turboshaft 800 HP

TABLE XId

ALTITUDE ENGINE TEST FACILITIES

WITH FREE JET TEST CAPABILITY

Facility/Cell Designation	Air Supply Flow (PPS)	Temp (^{o}F)	Pressure (PSIA)	Mach No.	Altitude (Feet)	Physical Size (Feet)	Thrust Stand (lbf)	Remarks
MAR, TC-2	400	-- +5000	1500	8.0	110,000	12D x 16L	100,000	Blowdown
MAR, TC-8	1200	-- +5000	300	4.7	100,000	14D x 80L	40,000	Blowdown
AEDC, T-1	800	-120 +650	35	3.0	80,000	12.3D x 75L	30,000	
AEDC, T-2	800	-120 +650	35	3.0	80,000	12.3D x 68L	30,000	
AEDC, T-4	800	-120 +650	35	3.0	80,000	12.3D x 55L	30,000	
AEDC, C2	1460	-100 +650	50	3.0	100,000	28D x 85L	75,000	Free Jet 1987 Transient Capa.
RAE (PYE), ATF-4	595	Amb. +872	44	3.5	100,000	30D x 69L	0	No Direct Connect
RAE (PYE), ATF-1	400	Amb. +422	132	3.5	100,000	12D x 122L	0	No Direct Connect
RR(BR), TP-131A	400	-- +841	165	4.2	90,000	10D x 80L	0	Blowdown

TABLE XId (Continued)

Facility/Cell Designation	Air Supply Flow (PPS)	Temp (^oF)	Pressure (PSIA)	Mach No.	Altitude (Feet)	Physical Size (Feet)	Thrust Stand (lbf)	Remarks
RR (DE), ATF-1	400	-113 +355	73	2.5	70,000	9D x 38L	20,200	
RR (DE), ATF-2	400	-113 +355	73	2.5	70,000	9D x 38L	20,000	
CEPr, R-5	825	-- +1200	100	4.0	65,600	18D x 100L	67,500	
CEPr, R-3	441	-85 +390	30	2.4	65,600	11.5D x 60L	45,000	
CEPr, R-4	441	-85 +390	30	2.4	65,600	11.5D x 60L	45,000	
US-ILA, HPT	154	-100 +350	28	2.2	65,600	10D x 33L	22,500	Transient Capa.
RAE (PYE), ATF-3	600	-100 +872	29	3.5	62,000	20D x 80L	50,000	Icing
CEPr, S1	221	-- +661	29	2.0	49,000	12D x 51L	22,500	
CEPr, C1	121	-86 +175	17	1.0	36,000	11D x 26L	2,250	
AEDC, APTU	1900	-- +1540	300	3.0	80,000	16D x 42L	50,000	Blowdown
RAE (PYE), ATF-3W	1390	-35 Amb.	Atmos	Sub	59,000	25D x 56L	50,000	

AIR CAPABILITY—ENGINE TEST FACILITIES

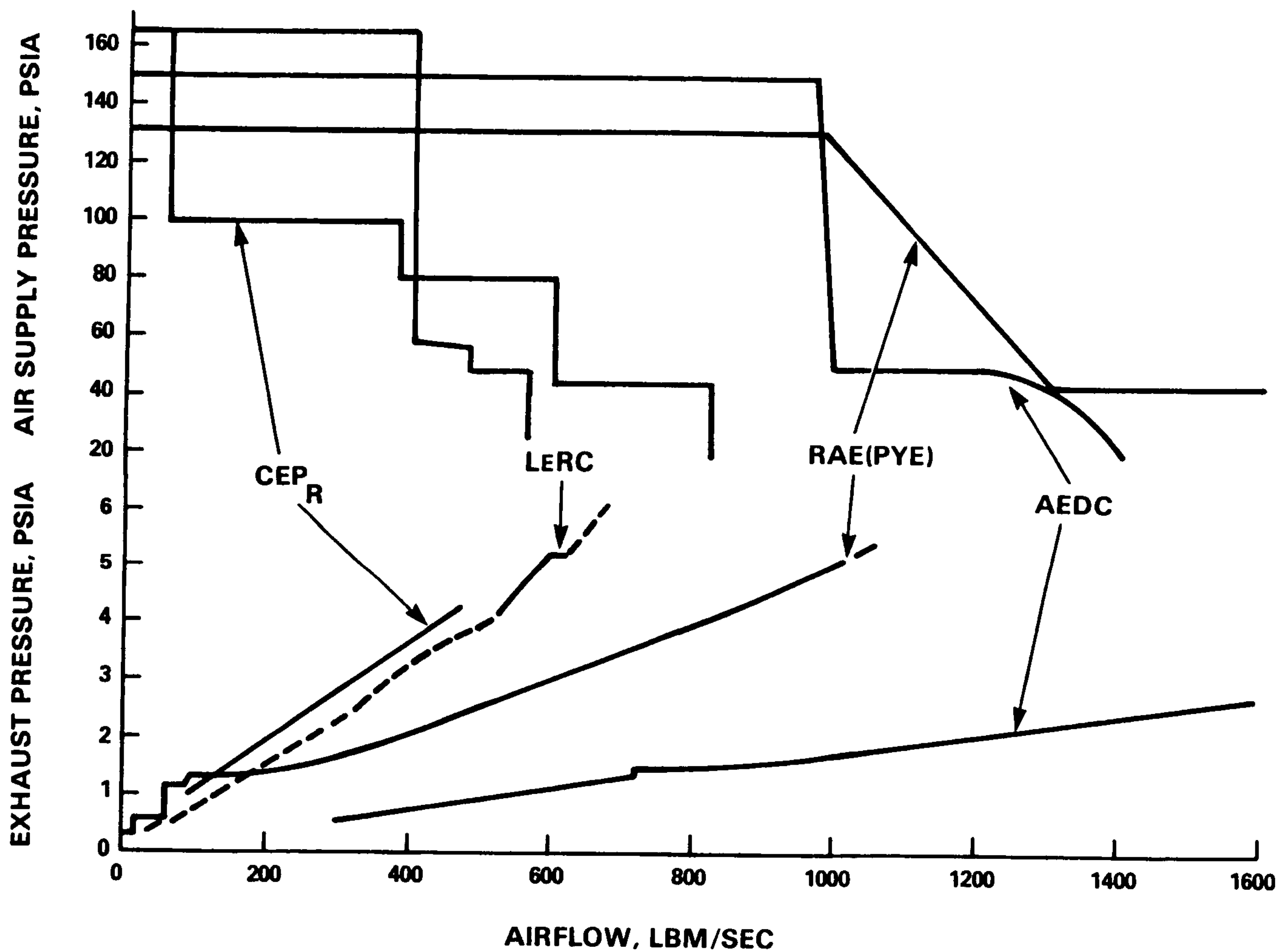


Figure 13

COMPARISON OF AIR HANDLING CAPACITIES

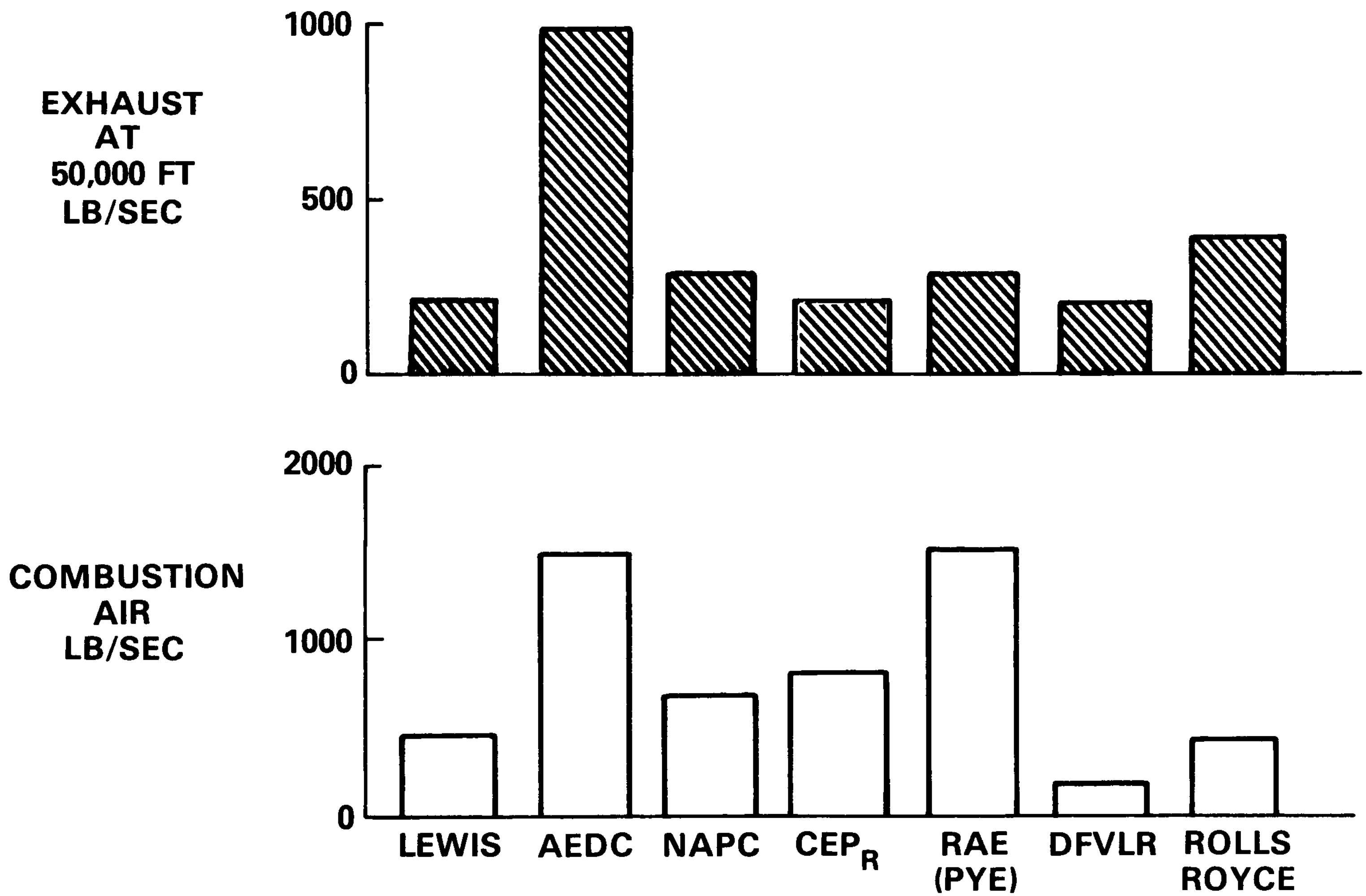


Figure 14

2.4 ENGINE/PROPULSION COMPONENT FACILITIES

The Engine/Propulsion Component facilities included in this assessment were limited to those for testing or conducting research on:

- Turbines
- Compressors
- Combustors

In contrast to propulsion wind tunnels and engine test facilities which require large complexes and usually large capital investments, component facilities are smaller, simpler, and considerably less costly. Whereas their bigger counterparts are principally used for the test and development of complete propulsion systems, component facilities are most often used for conducting the more basic and applied research plus experimental studies on propulsion subsystems, although a certain amount of development testing is also performed in them by engine manufacturers.

Of the component facilities reviewed, U.S. industry owns the major share, followed by NASA and the DOD. Universities own mostly small-scale, fundamental research facilities and rigs. While industry use of their facilities is mainly proprietary, they are also available for government R&D contract activity, as are the university ones. Forty-six U.S. facilities were reviewed representing a replacement value of about $250 M, not counting central air supply and utility systems. Due to the poor response from foreign installations, the number of foreign facilities reviewed was minimal, with Japan, the Netherlands, and West Germany the only respondents. However, the U.K.'s RAE-Pyestock and Rolls Royce facilities are familiar to the Assessment Team members and have been included in this comparison. Table I-b shows the distribution of these facilities by owners.

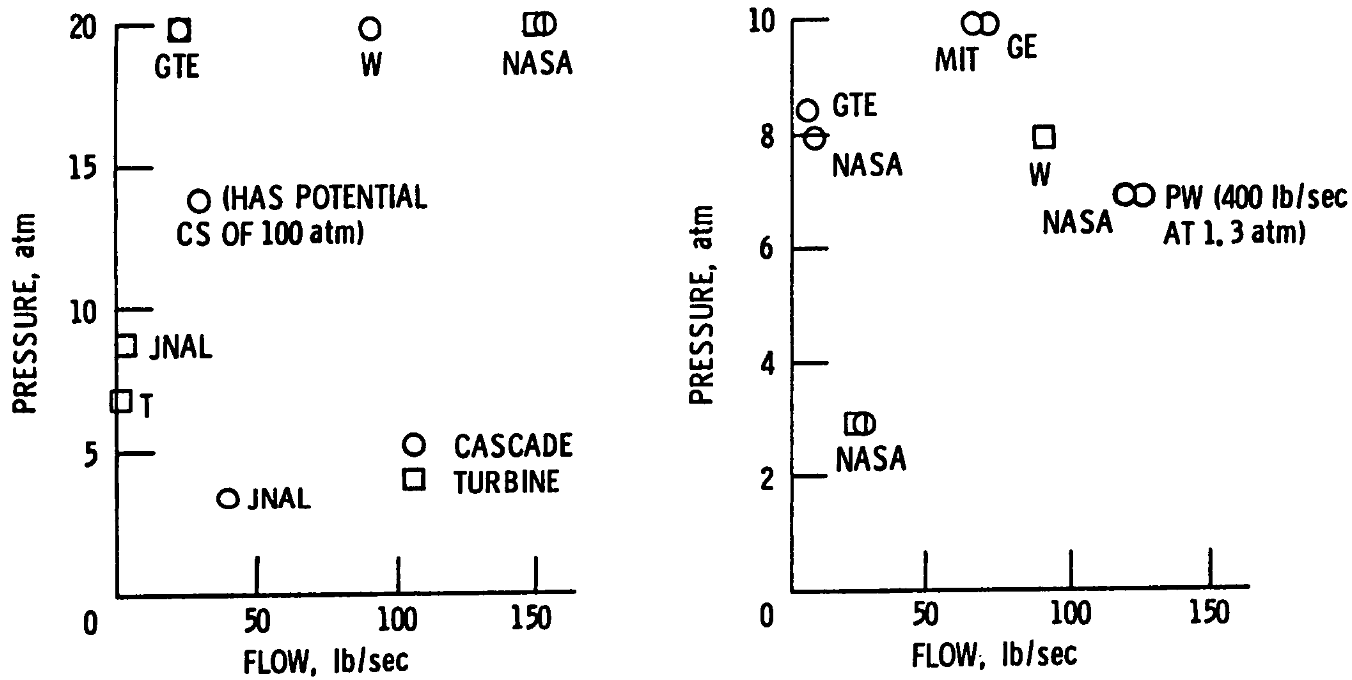
In assessing the relative capabilities of this class of facility, close attention and importance was given to a facility's versatility for conducting research as well as tests. For instance, a common research objective for all three types of facilities (turbines, compressors, combustors) is to provide the fundamental information needed to create computer modeling codes and then to verify the output of these codes. Detailed flow, pressure, stress, and heat transfer measurements on each of these components is therefore necessary, and the caliber of the instrumentation for conducting these measurements is as critical as the basic facility's characteristics of air flow, power, and temperature/pressure simulation. Unfortunately, performance comparison charts reflect only the latter and seldom address the other features, which are usually qualitative rather than quantitative. Nevertheless, an attempt was made to point out these features as qualifiers to the relative strengths and weaknesses otherwise indicated for the various facilities reviewed. For the most part these qualifications apply to the NASA Lewis facilities, which are primarily used for basic research.

2.4.1 TURBINE FACILITIES

A summary of the turbine facilities reviewed is provided in Table XII. Two plots comparing the relative capability within the U.S., NASA, and foreign facilities are shown in Figures 15a and 15b. These charts plot pressure versus flow for hot (2000 - 3000°F) and warm (600 - 1000°F) conditions. The general indication is that capabilities in this area are well spread within the U.S., with industry covering the broadest part of the test envelope. The situation in Europe and Japan is similar, with a variety of cold, warm, and hot rigs for static cascade and rotating stage research and development.

Although the U.S. industry facilities range from fundamental to developmental, they are used mostly in a proprietary manner to design and develop turbines specifically for their product lines. The NASA Lewis and university facilities are used primarily to address fundamental flow and heat transfer mechanisms, and the development of analytic models for fluid behavior.

Two Lewis facilities (one existing and one under construction) are unique, with capabilities beyond those of any other in existence. The Hot Section Facility (HSF) offers the highest flow capacity in both the



(a) Hot, 2000 to 3000 °F.

(b) Warm, 600 to 1000 °F.

GTE	GARRETT	JNAL	JAPAN NATIONAL AERO. LABORATORY
GE	GENERAL ELECTRIC	PW	PRATT AND WHITNEY AIRCRAFT
W	WESTINGHOUSE	T	TELEDYNE
NASA	LEWIS RESEARCH CENTER	CS	CALSPAN (SHOCK TUBE)

Figure 15. - Turbine facility capability.

cascade and turbine modes. The Small Warm Turbine facility has a unique combination of capabilities for testing and conducting research on small engine components. These include a rotating data system capable of reading pressures and temperatures, a flexibility for testing both radial and axial turbines, and the ability to duplicate real engine ratios of primary flow temperatures to coolant temperatures. The Hot Section Facility will be placed on standby in 1985, and the Small Warm Turbine facility will become operational in 1986.

2.4.2 COMPRESSOR FACILITIES

A summary of the existing compressor facilities reviewed is presented in Table XIII. A plot of the free world's overall capabilities in terms of speed, flow, and power is also shown in Figures 16a and 16b to highlight NASA's relative position. Although, as noted previously, the survey may not include all the domestic and foreign facilities in this area, it does bracket the full spectrum of existing capabilities in the free world, such that the mission facilities fall somewhere within the envelope covered by these plots. The indication is that U.S. industry owns the greatest capability in terms of the high power and flow capacity needed for large engine development work. The foreign facilities also appear oriented toward development work by emphasizing lower speeds but high power and flow capacity. In contrast, NASA's research capabilities extend over most of the rotational speed range but fall considerably short in power and flow. However, as also indicated earlier, these quantitative performance plots do not reflect the total capability in terms of unique instrumentation and data-gathering features crucial to fundamental investigations.

NASA Lewis' facilities are used to obtain detailed flow measurements within the blade passages of high speed turbines and compressors for use in modeling and code verification. As such, Lewis has acquired the finest overall capability in laser anemometry instrumentation that exists in the U.S. and the free world. The U.S. industry, in general, relies on NASA's research in this area. Only Pratt & Whitney pursues this type of

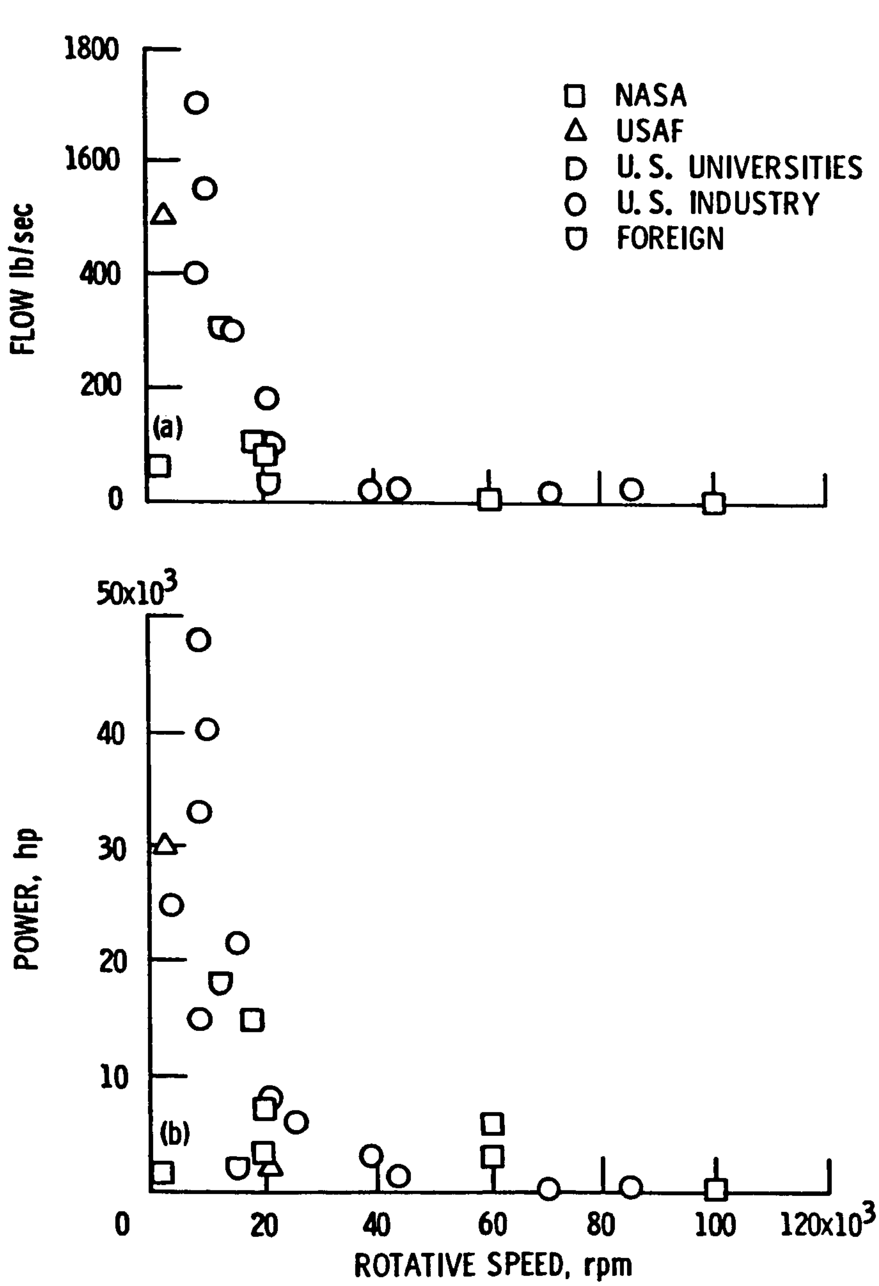


Figure 16. - Compressor facility capability.

work in-house. The U.K.'s Rolls Royce has an extensive program using laser instruments to study the internal flow fields of transonic axial stages, while Germany's DFVLR is pursuing similar studies on both axial and moderate pressure centrifugal stages. Other Lewis activities include detailed measurements of the stalled region within high speed multistage compressors, and studying the phenomenon of detuned rotors. The Large Low Speed Centrifugal Compressor Facility, scheduled for operation in 1986 will represent the only large facility of this type in the free world in which to conduct detailed flow measurement in its relatively large blade passages, and thereby improve the understanding of the complex flows within the three-dimensional, high viscous flow fields of centrifugal stages.

2.4.3 COMBUSTOR FACILITIES

As with the turbine and compressor facilities, the U.S. industry and foreign combustor facilities range from the fundamental research variety to the development types, but are principally used for proprietary, product-line improvement work. University and NASA facilities are more oriented to fundamental research. Table XIV lists the combustor facilities reviewed.

The advent of the modern gas turbine engine with combustion systems operating at high temperatures and high pressures has been accompanied by an increase in hot section durability problems, with the attendant need of upgrading combustor facilities to operate in these ranges. The U.S. industry has now upgraded their facilities to perform full pressure sector and reduced pressure, full annular testing. A comparison of the NASA, General Electric, and Pratt & Whitney capabilities for large combustor testing is shown in Figure 17. Also shown for comparison is the operating line for sector and full annular combustors, representing a typical modern, in-use, high-bypass ratio engine. Future cycles already in design will have operating lines even more severe than those shown. Both G.E. and P&W can test sector combustors at exact conditions. The LeRC Hot Section Facility (fully operational) can do likewise. However, at

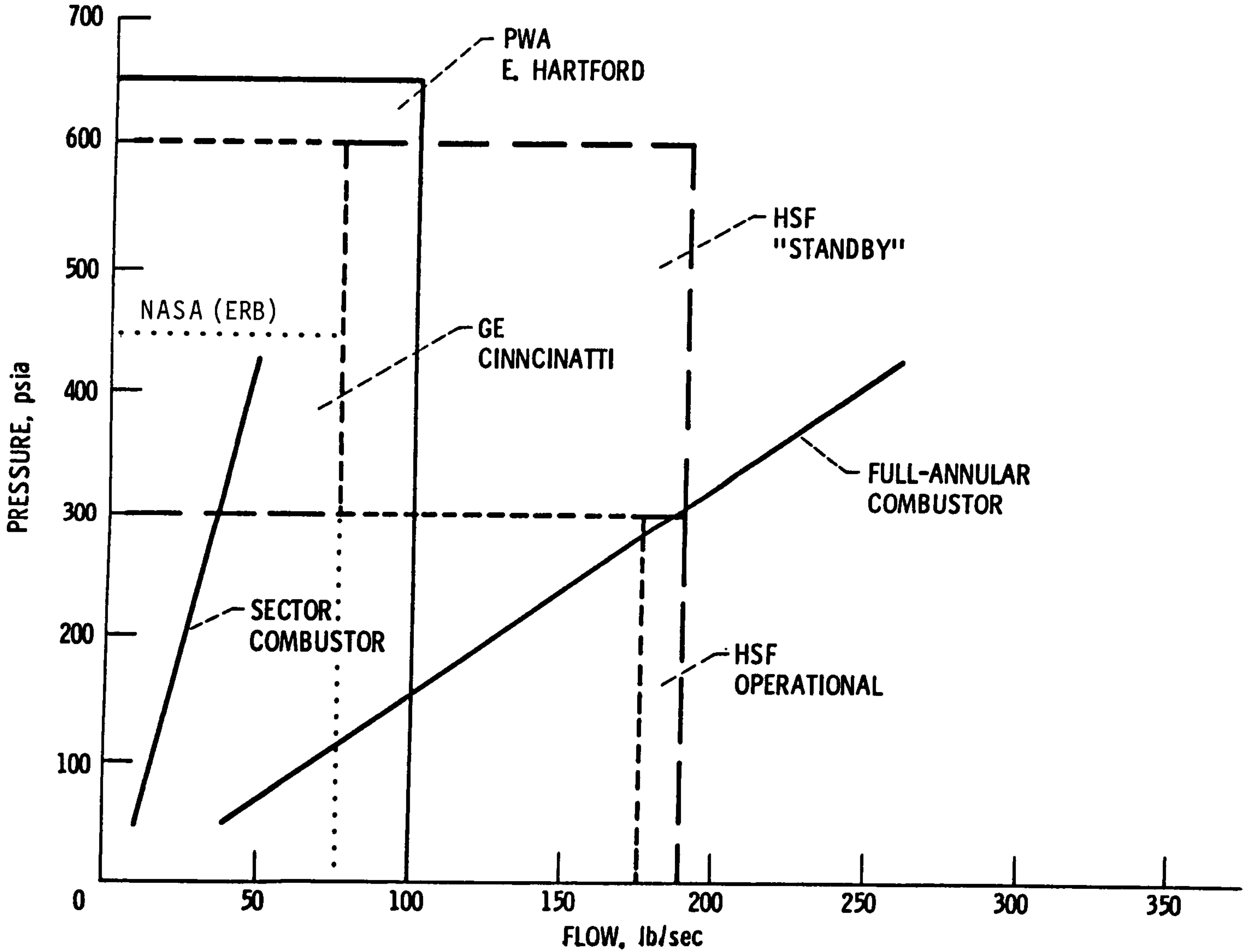


Figure 17. - Combustor Facility Capabilities

the present time none of the existing facilities has sufficient mass flow capability to handle the large, full annular combustors at maximum pressure. On the other hand, some versions of future generation engines, particularly those with bypass ratio in the 6 to 8 range, may have core flows substantially less than indicated in the chart, and fit well within the high end of the fully operational HSF flow map, making this facility a unique capability in the U.S. propulsion component arena.

With respect to foreign capabilities, the U.K., with the combination of Rolls Royce and RAE-Pyestock, has facilities comparable to the U.S.'s. The other European countries do not manufacture large engines and have not developed facilities with large flow capacity. In the Far East, Japan has continued the development of new combustion facilities, culminating in the activation of their 50 atmosphere, 8.8 lbs/sec combustor rig in 1983, for a very respectable capability.

2.4.4 SUMMARY

The development of advanced propulsion/engine components requires the use of facilities that are capable of providing fundamental information on their design characteristics and behavior across a wide spectrum of operating conditions. As such, these facilities tend to be much more research oriented than their engine and wind tunnel counterparts. Sophisticated instrumentation and computer modeling codes are as essential in this area of research and development as in any other, and future propulsion component facilities will require nonintrusive instruments such as laser anemometer, holography, and others that can accurately measure flow velocities, local gas and metal temperatures, and heat transfer. These measurements must be made in very close proximity to flow boundaries due to the criticality of boundary layer flow.

The most promising approach in successfully mapping the flow in these areas is through the use of very large compressors, fans, and turbines to provide boundary layers of sufficient thickness for thorough and accurate measurements. A large centrifugal compressor facility will exist at NASA

Lewis by 1986, but there will still be a need for a complementary large scale axial turbine facility to round out the research capabilities in this area, and NASA Lewis seems to be the logical place for it.

2.5 NASA'S POSITION IN AIRBREATHING PROPULSION FACILITIES

As stated previously, the Nation's premier capabilities in this category of aeronautical facilities resides mainly in DOD and industry. NASA's strength is located principally in its propulsion wind tunnels and some unique component research facilities. Its engine test capabilities are limited by air flow capacity, but are still of national caliber. Overall, NASA's principal asset and contribution to the Nation's strength in this field is its "total" research and test capability, which includes its research and operations staff in addition to the facilities themselves. Although this consideration applies also to the wind tunnels and flight simulators, it is particularly evident in the propulsion area. Its aero propulsion facilities are designed and operated to meet research needs rather than development requirements. Industry and DOD satisfy the latter quite well, but they both look to NASA to address the fundamental research and problem-solving needs across the entire spectrum of airbreathing propulsion. In this context, NASA is considered well facilitized, except for the specific needs addressed in this report plus the general recognition that some rehabilitation and modernization of its older facilities is a continuing necessity.

TABLE XII

TURBINE COMPONENT RESEARCH FACILITIES

FACILITY NAME/ LOCATION	MAX. FLOW RATE (lb/sec)	MAX. POWER (hp)	TEMPERATURE (^{o}F)	PRESSURE (atm. max)	SPEED (rpm)
NASA					
Lewis Research Center					
Turbine Heat Transfer Fundamentals Facilities	7	N/A	Atmospheric	Atmospheric	N/A
Hot Cascade 2D Cascade Facility	15	N/A	2500	8	N/A
Small Uncooled Turbine Facilities	2 1/2	45	150	3 1/2	45 000
Small Warm Turbine Facility	8	1250	800	8	60 000
High Pressure Turbine Hot Section Facility	200	35 000	2 500	20	23 000
Large Warm Turbine Facilities	25	5 000	950	3	25 000
Turbomachinery Aerodynamic Laser Anemometer Facility	10	N/A	Ambient	Atmospheric	N/A
INDUSTRY					
Garrett Turbine Engine Company					
(Cooled) Hot Turbine and Cascade Test Facility	22	3 000	2 800	20	43 000
Cold Air Turbine Mapping Facility	6	400	600	125 psia	60 000

TABLE XII CONT'D

TURBINE COMPONENT RESEARCH FACILITIES

FACILITY NAME/ LOCATION	MAX. FLOW RATE (lb/sec)	MAX. POWER (hp)	TEMPERATURE (^{o}F)	PRESSURE (atm. max)	SPEED (rpm)
General Electric					
Cell A7 Air Turbine Test Facility	70	15 000	100 - 1 000	8	15 000
Pratt & Whitney					
X-203 Test Stand	400; 125	10 000 - 20 000	-50 to +800	1.3; 7 atm	600 - 15 000
X-212 Test Stand	225; 125; 84	4 000 - 10 500	+1200	2; 8; 9 atm	5 000 - 15 000
Telydyne CAE					
Hot Cascade Test Stand	2	N/A	3 000	7	N/A
Turbine 1 and Turbine 2 Cold Flow Rig	25	300; 2400; 450	Ambient - 300	1.7	45 000; 23 000; 11 500
Westinghouse Combustion Turbine Systems					
Vane Cooling Development Rig	90	N/A	2 200	20	N/A
Aerodynamic Cascade Test Rig Row One Turbine Vane	90	N/A	900	8	N/A
UNIVERSITY					
Massachusetts Institute of Technology					
Blowdown Turbine Facility	64 200 scaled	2 000 52 000 scaled	500 4 000 scaled	10 40 scaled	7 000 14 000 scaled

TABLE XII CONT'D

TURBINE COMPONENT RESEARCH FACILITIES

FACILITY NAME/ LOCATION	MAX. FLOW RATE (lb/sec)	MAX. POWER (hp)	TEMPERATURE (^{o}F)	PRESSURE (atm. max)	SPEED (rpm)
JAPAN					
Ihi Mizuho Plant					
High Pressure Turbine Facility (HPT)	40	6 000	2 500	3.5	15 000
National Aerospace Laboratory					
High Temp Turbine Cooling Facility	3.7	N/A	2 200	9	N/A

TABLE XIII

COMPRESSOR RESEARCH FACILITIES

FACILITY NAME/ LOCATION	MAX. FLOW RATE (lb/sec)	MAX. POWER (hp)	TEMPERATURE (^{o}F)	PRESSURE (atm. max)	SPEED (rpm)
NASA					
Lewis Research Center					
Large Low Speed Centrifugal Compressor Facility	66	1 500	Ambient	Atmospheric Inlet up to 1.18 press. ratio	up to 2050
Transonic Oscillating Cascade Facility	950 ft/sec air velocity	1 150	Ambinet	Atmoshperic Inlet and Exhaust	--
Multi-stage Axial Flow Compressor Facility	100 (Ambient) 200 (Super-charging)	1 500	-70 to +150	0.3 - 5.3 inlet	up to 18 700
Small Multistage Compressor Facility	13	6 000	Ambient 1200 outlet temp	1.1 - 1.7 inlet plenum press up to 30:1 press ratio	up to 60 000
Small Centrifugal Compressor Facility	13	3 000	Ambient	0.1 - 1.0	up to 60 000
Small Single Stage Centrifugal Compressor Facility	2	Turbine Drive	+40 to Ambient	0.3 - 1.0 inlet plenum press	up to 100 000
Single Stage Axial Flow Compressor	100	3 000	Ambient	5 - 15 psia plenum press 3 - 14 psia collector press	up to 19 600
Coaxial Jet Facility	core: 30 fan: 30	--	core: 1 500 fan: 1 500	3:1 press. ratio	--
Fan Acoustic Facility	80	7 000	Ambient	Atmospheric Inlet/Exhaust up to 2.5 press. ratio	up to 20 000

TABLE XIII CONT'D

COMPRESSOR RESEARCH FACILITIES

FACILITY NAME/ LOCATION	MAX. FLOW RATE (lb/sec)	MAX. POWER (hp)	TEMPERATURE (^{o}F)	PRESSURE (atm. max)	SPEED (rpm)
DOD					
Wright Aeronautical Labs					
Compressor Test Facility	60	--	Ambient	1	6 000 - 21 500
Compressor Research Facility	500	30 000	Ambient	1	2 000 - 3 000
INDUSTRY					
Garrett Turbine Engine Company					
C-226 Compressor/ Fan Test Facility	30	600; 6 000	Atmospheric Inlet; 20 Exhaust	Atmospheric	85 000; 21 000
C-114, C-113 Compressor Test Facility	30	600; 6 000	Atmospheric Inlet; 20 Exhaust	Atmospheric	85 000; 21 000
Site A Fan Test Facility	180	8 000	Atmoshperic	2	11 000 - 21 000
General Electeric					
Full Scale Compressor Test Large Fan Test Facility (FSCT/LFTF)	1700 fan/ 400 Compressor	48 000	-70 to Ambient	Atmospheric	4 000 - 15 000
Pratt & Whitney					
B33A Stand	--	6 000	Ambient	Atmospheric	26 000
X-204 Test Stand	210; 400	21 600 max	-50 to +220	22.5"; 40" HgA	7 200 15 000
X-211 Test Stand	550	40 000	Ambient to 250	Atmospheric	5 000 - 10 989

TABLE XIII CONT'D

COMPRESSOR RESEARCH FACILITIES

FACILITY NAME/ LOCATION	MAX. FLOW RATE (lb/sec)	MAX. POWER (hp)	TEMPERATURE (^{o}F)	PRESSURE (atm. max)	SPEED (rpm)
Telydyne CAE					
3500 hp Compressor Test Stand	22	3 500	-60 to +110	1.5	39 000
1400-1 and 1400-2 Compressor Test Stands	22	1 200; 420	-65 to +235	1.5	42 000; 70 000
Westinghouse Combustion Turbine Systems					
Combustion Turbine Development Center		25 000			12 000 - 4 100
UNIVERSITY					
Massachusetts Institute of Technology					
Blowdown Compressor Facility	100 scaled	--	212 (max)	1	22 000
JAPAN					
National Aerospace Laboratory					
Fan/Compressor/ Turbine Facility	--	2 160	Ambient	Ambient	15 500
Large Scale Aero Engine Compressor Facility	310	18 000	Ambient	2	13 000

TABLE XIV

COMBUSTOR RESEARCH FACILITIES

FACILITY NAME/ LOCATION	MAX. FLOW RATE (lb/sec)	MAX. POWER (hp)	TEMPERATURE (^{o}F)	PRESSURE (atm. max)	SPEED (rpm)
NASA					
Lewis Research Center					
Low Pressure Combustor	A. 10 B. 3	N/A N/A	1 100 1 800	10 10	N/A N/A
Facilities					
Medium Pressure Combustor Facilities	20	N/A	Ambient - 1 100	30	N/A
High Pressure Combustor Facility (HPC)	200	N/A	Ambient - 850	20 operational 40 standby	N/A
DOD					
Wright Aeronautical Labs					
Combustion Research Tunnel	7 1/2	N/A	Ambient	Atmoshperic	N/A
INDUSTRY					
Garrett Turbine Engine Company					
C-100 Combustion Test Facility	18	N/A	60 - 2 000	20	N/A
Pratt & Whitney					
High Pressure Combustor Lab	100	N/A	450 to 1 200	44.2	N/A

TABLE XIV CONT'D

COMBUSTOR RESEARCH FACILITIES

FACILITY NAME/ LOCATION	MAX. FLOW RATE (lb/sec)	MAX. POWER (hp)	TEMPERATURE (^{o}F)	PRESSURE (atm. max)	SPEED (rpm)
Southwest Research Institute					
Army Fuels and Lubricants Lab, Combustor Test Facility	2.5	N/A	-65 to +1500	16	N/A
Telydyne CAE					
Combustor Cell	4; 22	N/A	-65 to +500	6; 1.7	N/A
Westinghouse Combustion Turbine Systems					
Full Scale Cylindrical Reverse Flow Rig	90	N/A	900	20	N/A
JAPAN					
Ihi Mizuho Plant					
Medium Pressure Combustor Facility (MPC)	24	N/A	180 to 780	7	N/A
National Aerospace Laboratory					
High Pressure Annular Combustor Test Facility	30	N/A	730	9	N/A
High Pressure Combustor Test Facility	8.8	N/A	Ambient - 850	50	N/A

3. FLIGHT SIMULATORS

3.0 INTRODUCTION

Unlike some aeronautical facilities (e.g., wind tunnels) which can be quantified across several parameters to cover a spectrum, there is no consistent methodology for quantifying flight simulation facilities. While simulators can be categorized by the makeup of the pilot station, the capability of the facility as a research and development tool is largely determined by the perceived research requirements for computing power, visual system capability, flight deck displays, motion cues, and air traffic control capability. Therefore, for the purpose of this assessment, a simulator facility is defined as the pilot station ("the simulator cockpit") and the support facilities required to provide the necessary information to the real-time piloted simulation. The decisions concerning what is necessary in terms of pilot perceptual cues and attendant computing requirements for a particular type of research or development are largely dependent on the individual R&D program. The flight simulation facilities have therefore been assessed based on capabilities to provide maximum information to the pilot and researchers.

The use of simulations in lieu of airborne flight operations is widespread in both R&D work and pilot training. The pilot training simulators offer distinct advantages in terms of reduced fuel costs, increased pilot training time, safety, and increased training efficiency. The R&D flight simulators are typically used in coordinated programs with wind tunnels, flight tests, and new avionics systems to develop new systems and concepts for aerospace vehicles. Although the new training systems are pushing the state-of-the-art, this assessment is only concerned with R&D flight simulation facilities. The training facilities are normally not available for R&D work and, in general, lack the flexibility and data acquisition capability necessary.

The R&D flight simulators included in this assessment cover a wide range of R&D work including:

- Handling qualities evaluation and control system design for proposed and existing aircraft.

- Avionics, Guidance and Navigation systems development, including controls and displays.

- Weapons systems development.

- Human factors studies including pilot capabilities and workload.

- Flight management including aircraft systems, flight procedures, and ATC interactions.

These facilities range from development simulators for specific new aircraft developments to generic flight decks offering significant capability in motion, visual, cockpit displays, or other support facilities.

Numerous R&D flight simulation facilities exist in the U.S. and abroad in both government agencies and private industry. These facilities range from a small CRT with a joystick at a desk to multimillion dollar research laboratories with powerful motion, visual, and computing capabilities. In an effort to identify the R&D flight simulation facilities with significant capabilities, a set of guidelines was generated for inclusion in the assessment. In addition, many R&D flight simulation facilities have more than one simulator cockpit (pilot station) and share support facilities among several cockpits. Computing facilities (including data acquisition and analysis tools), visual scene generation equipment (either CGI or model boards), and programmable display generators for Head-up or Head-down flight deck display (color or monochrome, stroke or raster) are typically shared facilities. In some cases, Air Traffic Control (ATC) facilities are available so that several different simulators can "fly" under ATC along with other computer-generated aircraft. The availability of these support facilities, as well as the power of the facility, was considered in making an assessment of the R&D capability.

Because the field of Flight Simulation is relatively new compared to wind tunnels and engine test facilities, large R&D Flight Simulation facilities are not as widespread or abundant as the others. This seems to be particularly evident in foreign countries. Also, unlike their sister aeronautical facilities, Flight Simulators are much more evolutionary due to the continually advancing electronics and computational systems on which they so strongly rely. This has created an environment of near-term obsolescence in all the existing facilities and even in those currently planned or under construction, with the older facilities suffering the most. On the other hand, those now emerging into this field, such as Japan, will enjoy the clear advantage that the latest technology will offer. It is in this context that the following assessment of relative capabilities must be taken. The dynamics of this environment will no doubt alter the picture in the near future.

Although a survey was made of all the domestic laboratories and industry known to be involved in R&D simulation, plus their foreign counterparts, the response was less than anticipated; particularly from the foreign countries. About 85 candidate facilities were received and examined, of which roughly 35 were eliminated for not meeting the set criteria. The numerous training facilities used by commercial airlines and the military were not included, nor were other facilities involved in other than aerospace R&D, such as the DOD's 40m visual system development simulator. Table I-c shows the distribution by owner.

Flight Simulation Facilities Categories: It is extremely difficult to place the numerous Flight Simulation facilities into several small categories, since most were designed for a specific research or development task. However, they can be fit into a few broad categories such as:

1. Airborne Simulation Facilities
2. High-Performance Aircraft Simulators

3. Vehicle-Specific Flight Decks
4. Generic Flight Decks

In this breakdown, most of the simulators surveyed fall into the last two categories. Nevertheless, these categories still permit a reasonable comparison and assessment of relative capabilities.

3.1 SUMMARY ASSESSMENT

The U.S. is the undisputed leader in this category of aeronautical facilities, although some good capabilities exist in the U.K., France, Germany, and Japan, with the latter currently building modern and very capable facilities. The U.S. leadership is generally across the board and resides mostly in the aircraft industry. NASA owns the premier capability in motion simulators with Ames' Vertical Motion Simulator (VMS) and Flight Simulator for Advanced Aircraft (FSAA). DOD's principal capability is its Total-In-Flight Simulator (TIFS), an airborne simulator operated from Wright Field.

3.2 AIRBORNE SIMULATORS

Although a number of government and military installations employ flying testbeds to evaluate new developments ranging from avionics to new engines, there are very few facilities classified as airborne R&D simulators. The U.S. has two exceptional airborne facilities which are configured for different types of R&D.

The Total-In-Flight Simulator (TIFS) operated by CALSPAN for the USAF WAL is basically a model-follower with on-board computers that can be programmed to provide the handling qualities of a range of different aircraft. It has the standard C-131 cockpit and a separate nose-mounted evaluation cockpit for R&D work. The TIFS is unique as a "flying simulator" which can be programmed to match the handling qualities of any aircraft within the limited envelope of the C-131 host aircraft.

The other unique "flying simulation facility" is the Terminal Systems Research Vehicle (TSRV) operated by NASA's Langley Research Center. The TSRV is designed for aircraft systems related efforts rather than handling qualities work. Although powerful on-board computers exist, no efforts have been made to change the basic B-737 handling qualities. The TSRV utilizes a flying simulator cockpit to do R&D on systems (controls, displays, flight management, ATC procedures, etc.) using the B-737's handling qualities. A ground-based simulator cockpit identical to the flight simulator cockpit is used with more powerful computers and cockpit display equipment to do preliminary studies. The ground-based simulator and the identical flying simulator represent a unique R&D simulation facility for systems work with fixed aircraft handling qualities but with programmable controls and displays.

The best capability for airborne simulators appears to be the ATTAS facility scheduled to be operational in 1986 in West Germany. The twin engine jet aircraft will combine the capabilities of the U.S. TIFS and TSRV with model following capability as well as an aft flight deck simulator in the aircraft and a ground-based simulator cockpit. The DFVLR facility will be used for handling quality as well as systems work. The facility will have an ATC capability to generate simulated traffic for systems studies.

The following were reviewed for this assessment:

- Terminal System Research Vehicle (TSRV) -- NASA Langley
- Total In-Flight Simulator (TIFS) -- USAF WAL
- NT-33A In-Flight Simulator -- USAF WAL
- BO-105 Fly-By-Wire Helicopter Simulator -- DFVLR, West Germany
- Advanced Technologies Testing Aircraft System (ATTAS) -- DFVLR, West Germany
- Helicopter Variable Stability Research (VSTAR) Vehicle -- NASA Ames
- Quiet STOL Research Aircraft (QSRA) -- NASA Ames
- VSTOL Flight Research Aircraft -- NASA Ames

3.3 HIGH-PERFORMANCE AIRCRAFT (AIR-TO-AIR) SIMULATORS

The air-to-air simulators are primarily used for high-performance aircraft with large fields-of-view. The dome projection techniques allow imagery to cover the pilot's entire field-of-view. Most existing facilities use servoed mirrors to project the other moving objects (aircraft, missiles, etc.) and servo-driven transparencies to project a full dome coverage terrain scene. The terrain scenes, however, lack the capability to project translation of the scene for altitude and speed cues. This major shortcoming of the air-to-air simulation facilities has recently been overcome by techniques to project computer-generated imagery (CGI) terrain scenes inside the domes. Several R&D and training facilities have initiated contracts for CGI terrain projection.

McDonnell Aircraft Company in St. Louis, Missouri, has the best overall capability for the air-to-air simulation facilities. In addition to having five domes capable of flying interactively, McDonnell has the most powerful computing facilities (CDC Cyber 170 series computers) and has awarded contracts for state-of-the-art capability in CGI terrain scene projection systems. There are also significant capabilities in air-to-air simulators in Europe in Germany, France, and England. The only air-to-air dome projection facility within NASA is the DMS at Langley. DMS was one of the first of these simulators, but has not been upgraded since it was built in 1969/70. The ACAVS at Ames will have a dome by 1987.

The following is the list of facilities reviewed under this category:

- Differential Maneuvering Simulator (DMS) -- NASA Langley
- Manned Air Combat Simulators (MACS) I, II, III, IV and V -- McDonnell Aircraft Co.
- LAMARS -- USAF WAL
- FHI Flight Simulator -- Fuji Heavy Industries, Japan
- Air Combat Simulator -- France
- Air Combat Simulator -- British Aerospace, England
- Dual Flight Simulator -- IABG, West Germany
- LASWAVES -- Northrop Aircraft

3.4 VEHICLE-SPECIFIC FLIGHT DECKS

The specific flight decks are intended for those R&D simulation facilities working on developments for a specific aircraft flight deck (e.g., a simulator working on developing controls, displays, and flight management functions for a company's next generation commercial transport). The facilities in this category range from the Boeing 737-300 developmental cab to advanced fighter development cockpits at McDonnell Aircraft and Mitsubishi (Japan) to helicopter simulator facilities at Bell to the shuttle hardware simulator at Rockwell. Each facility is designed for specific development work making comparisons difficult; however, Boeing probably has the best overall capability with a powerful set of computers, a state-of-the-art CGI system for out-the-window visual scenes, several developmental cabs (one with motion capability), and color cockpit display equipment. McDonnell Aircraft also has excellent facilities for development of fighter aircraft. The Europeans have excellent facilities in England and France; and the Japanese are building some good new facilities.

The list of Flight Decks in this category includes:

- Boeing 727 Flight Simulator -- NASA Ames MVSRF
- DC-9 Full Workload Simulator -- NASA Langley
- Hughes Advanced Fighter Simulator -- Hughes Aircraft
- Shuttle Hardware Simulator -- Rockwell
- Boeing 747 and 737-300 -- Boeing
- Boeing Systems and Workload Cab (B757-767) -- Boeing
- McDAC FA-18, AV-8B and GR-MK-V development simulation cabs -- McDonnell Aircraft
- Flight Simulator for R&D (FSRD) -- National Aerospace Labs - Japan
- Advanced Technology Fighter (ATF) Flight Simulator -- Japan - Mitsubishi

3.5 GENERIC R&D FLIGHT DECKS

The majority of the R&D simulator facilities fall into this category. Most of these facilities were designed to investigate a specific area of simulation making across the board comparisons difficult. Therefore, these facilities have been compared in the major categories of motion, visual, flight deck, and ATC capability as follows.

3.5.1 MOTION

In the area of motion capability, NASA Ames has the best overall capability with the Vertical Motion Simulator (VMS) with 60 ft. vertical and 40 ft. lateral motion capability, and the older Flight Simulator for Advanced Aircraft (FSAA) with 100 ft. lateral motion capability. The VMS system includes a family of interchangeable cabs to provide a variety of flight deck configurations, and multi-window CGI visual scene capability; plus a powerful CDC 7600 computer system. The addition of the Advanced Cab and Visual System (ACAVS) to the VMS in 1986 will provide dome projection of a state-of-the-art CGI (CT5A), plus highly modular rotorcraft-specific flight deck research capability. This integrated system represents a very powerful R&D simulation capability. Significant motion capability also exists in the USAF's LAMARS Simulator and the RAE's new Advanced Flight Simulator in the United Kingdom.

3.5.2 VISUAL

The best visual system capability lies with the latest generation CGI systems, which provide good scene resolution and realism, multiple moving objects in the scene and full color, daylight capability. These new CGI visual scenes are presented to the simulator pilot on projection domes for wide F.O.V. fighter aircraft, on multiple window systems for limited F.O.V. aircraft scenes (transports), and new partial dome systems for intermediate fields-of-view. A number of simulation facilities have acquired or contracted for these new CGI systems for essentially comparable visual system capability. The R&D facilities presently owning or acquiring the systems are: NASA Ames for the VMS/ACAVS facility, Boeing's Research Simulation Labs, McDonnell Aircraft's MACS facilities, Northrop's Simulation Labs, the USAF's Human Resources Labs, General Dynamics Simulation Labs, and Hughes Helicopter. The list is growing rapidly.

3.5.3 FLIGHT DECKS

The best capability for R&D involving the flight deck probably lies in the similar new facilities being developed as a joint project between NASA Langley, Ames, and Lockheed-GA. These new facilities have multiple CRT displays on the panel with programmable display generators which allow R&D on the displays. The facilities also have capability for R&D on the use of touchpanels, voice control and warnings, pilot control and display units (CDU), and other flight management and human factors functions. Other facilities with significant flight deck R&D capabilities include Boeing and Grumman in the U.S.A. and the Airbus facilities in France.

The following Generic Flight Decks were reviewed:

- Flight Simulator for Advanced Aircraft (FSAA) -- NASA ARC
- Vertical Motion Simulator (VMS) -- NASA ARC
- Adv. Concepts Flt. Sim. (ACFS) -- Lockheed-GA & NASA ARC
- Advanced Concepts Simulator -- NASA LaRC
- Visual Motion Simulator -- NASA LaRC
- Mission Oriented Terminal Area Sim. (MOTAS) -- NASA LaRC
- Multi-Crew Simulator -- USAF FDL-WPAFB
- Fighter/Bomber Simulator -- USAF FDL WPAFB
- Engineering Interactive Simulator -- Bell
- Multi-Purpose Cab -- Boeing, Seattle
- Engineering Flight Simulator -- Boeing Vertol
- Large Amplitude Research (LARS), Crew Station Technology Lab., and 6 DOF Simulators -- Grumman
- Man-Vehicle Systems Lab. (or ACFS) -- Lockheed-GA

- Large Amplitude (LAS), and Visual Flight (VFS) Simulators -- Northrop
- Engineering Development Simulator -- Sikorsky
- Air Traffic Mgmt. & Ops. Simulator (ATMOS) -- DFVLR, Germany
- Simulator for Aircraft R&D (SARD) -- Kawasaki, Japan
- Moving Base Flight Simulator (MBFS) -- Netherlands
- Advanced Flight Simulator -- RAE/Bedford, U.K.

3.6 NASA'S POSITION IN FLIGHT SIMULATORS

The state-of-the-art in simulation facilities has changed rapidly in the past five years. Two highly significant new developments have substantially changed requirements for simulation facilities. The use of the CRT in operational aircraft has grown to the point that almost all new or projected transport and fighter aircraft utilize the CRT in the cockpit to replace a substantial portion of the electro-mechanical instrumentation. Simulation facilities must now replace the electro-mechanical instruments and special purpose instrument drivers with color CRT's and programmable graphics systems in order to support most R&D activities.

The second major development lies in the area of out-the-window/canopy visual scenes. The latest generation CGI systems (E&S CT-5A, CT-6, and G.E. Compuscene IV) now provide the realism and resolution necessary to support many air-to-air and air-to-ground R&D activities. This eliminates many of the problems with visual scenes present in most simulation facilities. It is now possible to achieve wide F.O.V. scenes for transports or fighters with sufficient resolution. The tradeoff, up to now, has been to select either good resolution with narrow (limited) F.O.V. or wide F.O.V. with low resolution. These latest CGI systems coupled with new display techniques for windows or dome projection now allow increased use of simulation for R&D activities involving wide F.O.V.

The costs of upgrading to these new systems are substantial but ncecessary. Most U.S. R&D simulation facilities have spent $10 million to $50 million for upgrading facilities over the past three years and are continuing to spend at this rate. Almost all facilities have CGI systems in use or under procurement. NASA Langley is one of the few remaining laboratories with no wide F.O.V. (i.e., no CGI system) capability. Research planned for the DMS (high AOA aircraft control) and the TSRV and ACS facilities (terminal area flights, flight management studies) now require this high resolution, wide F.O.V. capability to carry out Langley's research mission. In the area of cockpit instrumentation systems, both Langley and Ames need to upgrade to color CRT displays in most simulator cockpits in order to support R&D activities related to new or proposed aircraft.

The only areas where NASA has outstanding capability in R&D simulation facilities are motion systems and advanced cockpits. The VMS at Ames with the ACAVS system installed provides the best motion facility in the U.S. or abroad. The Advanced Concept Facilities at Langley and Ames are on par with the best systems outside NASA. With the exception of these three facilities, NASA's R&D simulators are seriously obsolete. Most of the facilities are more than 10 years old. Ames' FSAA and Langley's real-time simulation I/O system and DMS are 15 to 20 years old and need upgrading or replacement. Langley's only motion capability is 14 years old and also needs replacement.

4. ASSESSMENT OF NASA'S CAPABILITIES AND NEEDS

4.0 INTRODUCTION

Based on the information presented previously, this section attempts the following:

- To identify those NASA aeronautical facilities that can be considered World Class, or of National stature.
- To determine the operational status or "health" of these facilities and what major upgradings or rehabilitations will be necessary between now and the year 2000 to maintain their "premier" classification.
- Provide input to an aeronautical facilities long range plan.

Each NASA facility in the three major categories covered by this assessment (wind tunnels, airbreathing propulsion, flight simulators) was evaluated and rated against those in the same subcategory (e.g., subsonic wind tunnels, engine test facilities, airborne simulators, etc.). Each facility was then assigned one of three classifications:

***World Class:	the best (or most unique) in the free world
**U.S. Class: (National)	a premier or unique capability in the U.S. but not worldwide
*NASA Only:	a unique or best capability within NASA.

This classification is intended to indicate a facility's importance in maintaining this Nation's preeminence in aeronautical R&D, and therefore the need for retaining its capability through the foreseeable future. Combined with other factors such as age, state of repair or obsolescence, replacement cost, and level of use (demand), some conclusions can be drawn about the particular NASA facilities that need rehabilitation and/or upgrading within the next 15 years, plus the relative priorities. It must be realized, however, that a given classification is not necessarily static since it reflects today's conditions and situations for a particular facility and its peers. Modifications to upgrade that facility's capabilities or the construction of new and better capabilities somewhere else may alter this classification in future years.

For each of the major categories, the respective facilities have been listed by Center and by subcategory in a matrix format that indicates the age, replacement cost, previous upgrades, and operational status of each facility, plus its rating classification. Comments also have been added for each indicating a key characteristic of that facility and/or its need for upgrading or rehabilitation. These matrices provide a quick reference from which to glean the observations and recommendations made for each of the facilities categories.

4.1 WIND TUNNELS

There are 39 wind tunnels in NASA meeting the criteria discussed in Section 1, with an average age of 30 years and a total replacement value of around $1.4 B. This represents roughly one-third of the U.S. wind tunnel population and about half of their total replacement value of $3 B. In contrast, the average age of DOD's wind tunnels is 24 years, industry's is also 24 years, and over 40 years for academia. The latter, however, have mostly been renovated more recently. The matrix listing the NASA wind tunnels by Center and speed regime is shown in Table XV.

4.1.1 SUBSONIC TUNNELS

Of the 11 tunnels in this category at NASA, 7 were built in the 1940's and one in 1930. The latter is the 30x60 ft. Full Scale Tunnel at Langley which is currently undergoing some upgrading, but whose main structure and drives are still 50 years old. The Ames 40x80x120 is the largest and most expensive complex. Although the 40x80 circuit was

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TABLE XV

NASA WIND TUNNELS MATRIX

FACILITY	PREMIER CLASS	YEAR BUILT	REPLACE. COST ($M)	YEAR (S) UPGRADED	OPERATIONS # SHIFTS	COMMENTS
AMES						
Subsonic Tunnels						
80X120	***	1986	230	1936	Oper. 1986	Largest Tunnels in Free World. Will need additional Mods
40X80	***	1944				
12 Ft. PWT	***	1946	38		2/Day	Good Flow; Hi Re, Needs upgrade
7X10 Ft.		1941	4	74/82	1/Day	V/STOL
Transonic Tunnels						
14 Ft.	**	1956	58		Standby	Unique Visual Capabilities; Needs Rehab.
11 Ft. (Unitary)	***	1956	146 (1)	1976	3/Day (2)	Heavy backlog
2X2 Ft.		1951	9			Needs Relocating
Supersonic Tunnels						
9X7 Ft. (Unitary)	***	1956	146 (1)		3/Day (1)	Heavy use. Need upgrading
8X7 Ft. (Unitary)	***	1956				
6X6 Ft.	*	1943			1/Day	Broad Speed Range
Hypersonic Tunnels						
3X5 Ft.	***	1960	35	1972	Standby	Heater Dome Replaced
11		Avg: 1954	$561M			

(1) Cost and Schedule includes all Unitary Tunnels

TABLE XV Cont'd

FACILITY	PREMIER CLASS	YEAR BUILT	REPLACE. COST ($M)	YEAR(S) UPGRADED	OPERATIONS # SHIFTS	COMMENTS
LANGLEY						
Subsonic Tunnels						
30X60 Ft.	**	1930	19	73/84	2/Day	Unique Open Throat -- Low Speed
4X7 M	**	1970	18	1984	2/Day	V/STOL Heavy Use
7X10 Ft.	*	1945	14		1/Day	
Low Turb. Pressure	***	1940	9	1981	1/Day	Excellent Flow - Research Tool; Backlog
Vertical Spin	***	1940	1.5	1984	2 1/2/Day	Heavy Use
Transonic Tunnels						
16 Ft.	**	1941	83	75/85	2/Day	Propulsion Integration - Backlog
8 Ft. TPT	***	1953	40	1980	1/Day	Excellent Flow
0.3M	*	1973	2.5	1978	2/Day	" "
6X28 In.		1938	4		1/Day	Research Tool
NTF	***	1982	136		1 1/2 Day	Initial Operation - Needs Some Upgrading
TDT	**	1959	57	80/83	2/Day	Flutter Research
Supersonic Tunnels						
Unitary Plan	**	1954	150	1979	2/Day	Will Need Motor Rewinding
Hypersonic Tunnels						
8 Ft. HTT	***	1964	41	80/85	1/Day	Heavy Use - Large Backlog
20 In. Mach 6	*	1958	38(1)		1/Day	
CF_4	***	1972	8		1/Day	
Continuous Flow		1962	24	1984	1/Day	New Throat in '84
Hypersonic He		1958	49(2)	1969	1/Day	Aero Leg Addition in '69
Hyersonic N_2	**	1964	49(2)		1/Day	
Mach 20 Ri Re He	***	1952	49(2)	1951	1/Day	
Mach 8 Var. Density		1952	38(1)		Standby	
Mach 6 Hi Re	***	1958	38(1)		1/Day	
Scramjet	***	1974	49(2)		1/Day	
22	Avg:	1956	$676M			

(1) Cost Includes All These Tunnels

(2) Cost Includes All These Tunnels

TABLE XV Cont'd

FACILITY	PREMIER CLASS	YEAR BUILT	REPLACE. COST	YEAR (S) UPGRADED	OPERATIONS # SHIFTS	COMMENTS
<u>LEWIS</u>						
Subsonic Tunnels						
9X15 Ft.	**	1968	9		4/Wk.	Backleg of 8X6 W.T.
IRT	***	1944	40	1984	6/Wk.	Icing
Supersonic Tunnels						
10X10 Ft. Prop.	***	1955	70		6/Wk.	Needs Rehab., Upgrading
8X6 Ft. Prop.	**	1948	66		6/Wk.	Needs Rehab.
1X1 Ft.	*	1954	1.5	81/83	6/Wk.	
5		Avg: 1954	$187M			
<u>MSFC</u>						
Transonic Tunnels						
Hi-Reynolds	**	1969	2		1/Day	Very High Reynolds
Total 39		Avg: 1955	$1,426M			

*** World-Class Facility
** US-Class Facility
* NASA Class

built in 1944, it was recently enlarged with an 80x120 ft. leg and is now in the process of final modifications before its scheduled operation in 1986. An analysis of each subsonic tunnel follows:

a. World Class Subsonic Tunnels:

ARC: 40x80x120: Will still need acoustical treatment of its 80x120 test section, leg, and inlet to meet research needs and environmental restrictions (1988-1990 time frame). Powered model testing will otherwise be severely restricted.

ARC: 12 Ft. PWT: Needs modernizing of its antiquated test section model support and model handling capabilities (1990). Urgent need of pressure shell recertification to prevent downrating of its operating pressure level (now). The tunnel is in high demand by the U.S. industry due to its excellent flow quality and high Reynolds number capability.

LRC: Low Turbulence Pressure Tunnel (LTPT): This tunnel was recently upgraded and now offers the best flow of any other research tunnel in its class. No other major upgrades contemplated.

LRC: Vertical Spin Tunnel: The largest and probably the most used tunnel in its class. Underwent minor rehabilitation in 1984. No major upgrades foreseen.

LeRC: Icing Research Tunnel (IRT): This is the largest tunnel in the world dedicated to icing research and therefore is in high demand. It is currently undergoing major rehabilitation to improve its water/icing spray mechanism and temperature controls. No additional major improvements are anticipated.

b. U.S. Class Subsonic Tunnels:

LRC: 30x60 Full Scale Tunnel: This is the second largest wind tunnel in the free world with a unique "free-flight" model support system. Its low speed limitations prevent it from being classified in the World Class category, but it is clearly a U.S. premier facility. It is undergoing modifications of its model support and turntable system plus its control room instrumentation. No additional upgradings are contemplated, but its structure is over 50 years old and may need rehabilitation within the next 15 years.

LRC: 4x7 Meter (V/STOL) Tunnel: This tunnel was modified in 1984 to improve its flow quality and productivity and to acoustically treat the test section. It is now one of the best tunnels in the Nation for conducting subsonic aerodynamic and rotorcraft tests, including powered models. Future needs include acoustically treating a much larger section of the wind tunnel circuit to lower its background noise significantly (-30 db by 1990).

LeRC: 9x15 Ft. Propulsion W.T.: This tunnel is the back leg of the 8x6 tunnel, added in 1968. It is one of about six low speed propulsion wind tunnels in the world, and although not of World Class caliber in its overall capabilities, it is currently the best available in the U.S.. This tunnel leg per se is not in need of major rehabilitation, but the basic 8x6 tunnel is. The latter is covered in the supersonic tunnel discussion.

c. NASA Class Subsonic Tunnels:

ARC: 7x10 Ft.: This facility has been the workhorse of the Ames low speed tunnels for conducting V/STOL, rotorcraft work in the absence of the 40x80x120. No major modifications are contemplated.

LRC: 7x10 Ft.: Although equal in size to the Ames tunnel, this facility operates at much higher speeds and varying temperature conditions. Some rehabilitations may be necessary within the next 10 years.

4.1.2 TRANSONIC TUNNELS

NASA owns 10 tunnels in this speed regime, 6 of which are at Langley. Three are of World Class caliber and another four are among the best in the U.S.. NASA's capabilities in this category are now the best in the free world, particularly with the addition of the NTF. This set of NASA tunnels is generally newer than its subsonic ones, with an average age of 26 years, including the NTF which was completed in 1982. Most of these have already undergone some upgrading over the past 10 years and are generally in good shape. Langley's 16 ft, built in 1941, is also scheduled for rehabilitation in FY 1986.

a. World Class Transonic Tunnels:

ARC: 11 Ft.: This is the transonic leg of Ames' Unitary Plan Tunnels. It was modernized in 1976 with a new data aquisition system to improve its productivity, but it is still one of the busiest tunnels in NASA's inventory. No additional modifications are projected for the foreseeable future.

LRC: NTF: This new facility is now the premier transonic wind tunnel in the free world for conducting full scale high Reynolds number research. Modifications of its model support system will be required in the near future to permit a wider range of angle of attack positions, particularly for high performance aircraft model tests. Additional improvements or modifications to this facility may be required within the next 15 years as more operational experience is acquired.

LRC: 8 Ft.: TPT: This facility was modified in 1980 to upgrade its flow characteristics. It is now one of the best transonic tunnels in the free world for conducting low turbulence, laminar flow research. No additional modifications are contemplated, although it is a 30-year-old facility which may require some systems and structural overhauling by the year 2000.

LRC: TDT: This is Langley's other 16 ft. tunnel, specializing in aeroelasticity and flutter research. It is 18 years younger than the 16 ft. tunnel and has already undergone major rehabilitation in 1983. No further improvements are anticipated in the foreseeable future.

b. U.S. Class Transonic Tunnels:

ARC: 14 Ft.: Because of the high demand for its 11 ft. tunnel, this facility has become the workhorse for the Ames in-house research. It also offers special features such as optical ports which are unique in NASA and the U.S., and therefore essential for certain types of DOD work. The facility is about 30 years old and in serious need of overall rehabilitations. It is currently on standby status.

LRC: 16 Ft.: Currently scheduled to undergo rehabilitation in FY 86 to increase its productivity and research capabilities, this is Langley's busiest transonic tunnel. Its high demand is due to its size and its propulsion/airframe integration research capabilities, surpassed only by AEDC's 16 T.

MSFC: High Reynolds Tunnel: Although a very small tunnel (3 ft.) for this speed regime, it offers excellent Reynolds number capabilities and good flow characteristics. No major improvements are contemplated.

c. NASA Class Transonic Tunnels:

LRC: .3 M Tunnel: This is the pilot facility for the NTF and still an excellent basic research tool for NASA. No major improvements are contemplated.

ARC: 2 Ft.: Tunnel: This is a good 2-D research tunnel for NASA, but needs relocating from its present site in the courtyard of the 40x80x120 complex, and needs some rehabilitation within the next five years.

4.1.3 SUPERSONIC TUNNELS

There are seven supersonic wind tunnel facilities in NASA, including the Unitary Plan W T at Langley, which are actually two tunnels, and the two propulsion tunnels at LeRC. Most were built in the fifties and are now in need of some upgrading or rehabilitation. Of the seven tunnels, Ames' Unitary Plan Tunnels and Lewis' 10x10 propulsion tunnel are considered World Class facilities, mostly because of their size. The other Lewis propulsion tunnel (8x6 ft.) is considered U.S. Class, principally for its propulsion capability.

a. World Class Supersonic Tunnels:

ARC: Unitary Plan Tunnels (9x7 & 8x6 Ft.): Both of these tunnels are considered World Class facilities because of their size and good Reynolds number capability. However, they are in need of general modifications to update their instrumentation and productivity. This upgrading will be necessary within the next 5 to 10 years.

LeRC: 10x10 Ft. Propulsion Tunnel: This is the second largest supersonic propulsion tunnel in the free world (after AEDC's 16 S). It is a 30-year-old facility with no previous rehabilitation or upgrading and in need of some overhauling within the next five years, particularly its drive motors.

b. U.S. Class Supersonic Tunnels:

LeRC: 8x6 Ft. Propulsion Tunnel: Except for its overall need for rehabilitation and modernization, this 36-year-old facility could be of World Class caliber. It is one of a very small number of supersonic propulsion tunnels in the world and the only one with a speed range also covering the subsonic speed regime. The 8x6 and the 10x10 complement one another in Mach number range, with the 10x10 covering the high end of the supersonic spectrum. As indicated, this facility is in serious need of rehabilitation, which should be accomplished within the next five years.

c. NASA Class Supersonic Tunnels:

ARC: 6x6 Ft. Tunnel: This is a unique tunnel within NASA in that it covers a wide range of speeds from the low subsonic through the supersonic. It is Ames' workhorse for in-house basic research that cannot be scheduled on the very busy Unitary Plan Tunnels. There are no major improvements or modifications envisioned for this facility in the next 5 to 10 years.

LRC: 4x4 Ft. Unitary Plan Tunnels: These tunnels are the Langley equivalent of the Ames 6x6, in that they carry the burden of Langley's fundamental research in this speed regime. These busy 30-year-old tunnels were rehabilitated in 1979, and there are no plans for additional major improvements in the foreseeable future.

4.1.4 HYPERSONIC TUNNELS

Except for the 3.5 ft. tunnel at Ames, all of NASA's hypersonic facilities are at Langley. These consist of the large scale 8 ft. High Temperature Tunnel, the 4 ft. ramjet propulsion facility, and several (8) tunnels situated at various locations throughout the Center but comprising a logical "hypersonics complex" covering a broad range of capabilities in this speed regime. Individually, these tunnels range from World Class to average. However, as a group, they are unsurpassed in the free world. Averaging a little over 20 years in age, these tunnels are in serious need of rehabilitation if they are to serve this country's technology needs for the coming century. Some of these facilities are now on standby and are undergoing some upgrading as discussed below.

a. World Class Hypersonic Tunnels:

ARC: 3.5 Ft. Tunnel: In size and Reynolds number capability this is a premier facility, although it has a limited Mach number range (<10). It is currently on standby awaiting the installation of a new heater dome liner. Possible upgrading of this tunnel includes increasing its Mach number range to 14 within the next 5 to 10 years.

LRC: 8 Ft. High Temperature Tunnel: This tunnel was originally built and used as a high temperature structures facility but is currently undergoing modifications to also allow ramjet/scramjet propulsion tests. The Mach number range is also being modified for lower speeds (Mach 4), along with a general rehabilitation of this 20-year-old facility. When completed, it will be the world's largest, long-duration blow-down hypersonic propulsion facility in the free world. It is also one of the candidate facilities for supporting the research and development needs of future (21st century) hypersonic vehicles.

LRC: Hypersonic Facilities "Complex": Of the remaining set of tunnels in this speed regime at Langley, the following are of World Class caliber based on their individual merits:

- CF4 Tunnel
- Mach 20 High-Reynolds Helium Tunnel
- Mach 6 High-Reynolds Tunnel
- Scramjet Propulsion facility

As indicated above, these facilities and the rest of the "complex" are in need of general rehabilitation if they are to continue serving this country's needs into the next century.

b. U.S. Class Hypersonic Tunnels:

LRC: Hypersonic Nitrogen Tunnel: Of the remaining hypersonic facilities, the Nitrogen tunnel is unique by virture of its N_2 environment and therefore is considered of U.S. Class caliber.

c. NASA Class Hypersonic Tunnels:

LRC: Since all of the remaining tunnels are at LRC, this is a meaningless distinction. However, as indicated previously, these tunnels must be considered as a set in order to properly evaluate their worth to the Nation's capability in this speed regime. As also indicated previously, the entire complex must be examined for rehabilitation or for a decision to entertain a new approach (facility) for conducting hypersonics research leading to 21st century vehicles.

TABLE XVIa

NASA PREMIER WIND TUNNEL FACILITIES

WORLD CLASS TUNNELS	Year Built	Replacement Cost ($ M)	Rehabilitation/Upgrade Needed
Subsonic:			
ARC - 80x120 ft	1986)		In Progress
- 40x 80 ft	1944/86)	230	Possible Acoustical Treatment
- 12 ft PWT		38	Pressure Shell Recert. - Overall Upgrading
LRC - Low Turbulence Pressure	1940	9	None
- Vertical Spin	1940	1.5	None
LeRC - IRT	1944	40	In Progress
Transonic:			
ARC - 11 ft Unitary	1956	*146(1)	None
LRC - 8 ft TPT	1953	40	None
- NTF	1982	136	Model Support System
Supersonic:			
ARC - 9x7 Unitary)			Model Preparation Area
- 8x7 Unitary)	1956	*146(1)	Instrumentation
LeRC - 10x10 ft Prop.	1955	70	Motors Remount; Model Support Increased Speed
Hypersonic:			
ARC - 3.5 ft	1960	35	Complete Heater Bed Replacement; Mach Number Increase
LRC - 8 ft HTT	1964	41	In Progress
- CF_4	1972	8	Part of Hypersonic Complex Rehab.
- Mach 20 Hi-Re He	1952	* 49(2)	Part of Hypersonic Complex Rehab.
- Mach 6 Hi-Re	1958	* 38(3)	Part of Hypersonic Complex Rehab.
- Scramjet Prop.	1974	* 49(2)	Part of Hypersonic Complex Rehab.

TABLE XVIb

NASA PREMIER WIND TUNNEL FACILITIES

U.S. CLASS TUNNELS	Year Built	Replacement Cost ($ M)	Major Rehabilitation/Upgrade Needed
Subsonic:			
LRC - 30x60 ft	1930	19	In Progress
- 4x 7 m	1970	18	None
LeRC - 9x15 Prop.	1968	9	Part of 8x6 ft Tunnel Rehab.
Transonic:			
ARC - 14 ft	1956	58	Overall Rehabilitation
LRC - 16 ft	1941	83	In FY 86 Budget
- TDT	1959	57	None
Supersonic:			
LRC - Unitary	1954	150	None
LeRC - 8x6 Prop.	1948	66	Motor Rewinding - In Progress Overall Rehab.
Hypersonic:			
LRC - Hypersonic N_2	1964	*49(2)	Part of Hypersonic Complex Rehab.

(1) Total cost for ARC Unitary Plan Wind Tunnels
(2) Total cost for several facilities in same building
(3) Total cost for several facilities in same building

TABLE XVII

NASA PREMIER WIND TUNNEL FACILITIES

DISTRIBUTION BY CENTERS

World Class	ARC	LRC	LeRC	Total
Subsonic	3	2	1	6
Transonic	1	2	-	3
Supersonic	2	-	1	3
Hypersonic	1	5	-	6
	7	9	2	18
U.S. Class				
Subsonic	-	2	1	3
Transonic	1	2	-	3
Supersonic	-	1	1	2
Hypersonic	-	1	-	1
	1	6	2	9
	8	15	4	27

4.1.5 WIND TUNNELS SUMMARY

Of the 39 wind tunnels owned by NASA, 18 are considered World Class facilities and 9 are at least of U.S. Class caliber. As indicated in Table XVII these are mostly at Langley, although 7 of Ames' 11 tunnels are World Class. All of Lewis' propulsion tunnels are either of World or U.S. Class caliber. These statistics also indicate that NASA's wind tunnel facilities represent a principal asset in the Nation's (and the free world's) aeronautical R&D capability across all speed regimes. However, of these 27 premier facilities, representing a current capital investment of about $1.3 B, at least 11 (with a capital value of about $450 M) are in need of major rehabilitation or upgrading within the next 15 years; some as urgently as the next 5 years.

4.2 AIRBREATHING PROPULSION

The Agency's airbreathing propulsion capability is now concentrated principally at Lewis, with a relatively small capability at Langley in the hypersonic propulsion area (ramjet/scramjet). The latter's two propulsion tunnels in this speed regime are the 4 ft. ramjet and 8 ft. high temperature tunnels. These are unique capabilities that have already been covered in the Wind Tunnel section and will not be repeated here. On the other hand, Lewis' three propulsion wind tunnels are listed again in this section for the sake of displaying LeRC's total capability across the entire spectrum of propulsion facilities.

In addition to their three propulsion wind tunnels, Lewis' aero propulsion capabilities also include four altitude engine test stands and numerous engine component test cells and rigs, of which only 18 have been included in this assessment as meeting the set criteria (mostly size or cost). Table XVIII lists the matrix for these three categories, indicating a replacement value for the listed facilities of about $440 M, to which approximately $250 M is added for the entire Engine Research Building (ERB) complex where all the component test facilities, air supply system, and other supporting equipment are contained. This aggregate investment of about $700 M at Lewis represents only their principal facilities and does not account for all of the lesser rigs and laboratories plus the remaining supporting systems. By comparison, the comparable investment by DOD is about $2 B (including ASTF and their two large propulsion wind tunnels), and about $1 B for industry.

a. World Class Facilities:

Wind Tunnels: 10x10 Ft. Propulsion WT - One of the world's largest supersonic propulsion tunnels. In need of some upgrading to extend its Mach number range.

Components: Small Warm Turbine Facility - A new and unique facility under construction to study the flow characteristics and the structural/mechanical characteristics and behaviors of small turbine engines components. This facility should not require any major modifications till the year 2000.

High Pressure, Hot Section Facility - This facility, better known as the HPF, has recently been placed on standby status. It offers one of the best capabilities in the world for testing turbine engine "hot sections" (e.g., turbine and combustors). The full potential capabilities of this facility should be maintained, at least on a "ready" status.

Large Low Speed Centrifugal Compressor - This potential World Class facility is also under construction with an operational readiness date of 1986. It will provide the capability, not currently available anywhere, to perform fundamental studies on the internal flow characteristics of compressor stages and individual blades.

b. U.S. Class Facilities:

Wind Tunnels: 9x15 Ft. and 8x6 Ft. Tunnels - Both of these tunnels offer unique capabilities unavailable anywhere else in the U.S. and are discussed in more detail in the Wind Tunnel section.

Engine Test Facilities: Propulsion System Laboratory (PSL) - Lewis' altitude engine test capabilities reside exclusively in its PSL complex. This complex has four test cells, two of which, PSL-1 and 2 (the oldest), are currently deactivated. The two newer ones, PSL-3 and 4, are very active facilities but limited by air flow capacity to testing turbojet or medium size turbofan engines. For this reason they are not judged here as World Class facilities in the same context as the AEDC or major industry facilities. Nevertheless, as research and problem-solving tools for other than the large, high bypass, turbofan engines, the PSL complex is in high demand for cooperative DOD and industry work.

The PSL's air flow capacity of 480 lbs/sec is only marginal for testing large turbojet or even small high bypass turbofan engines. An increase of the Lewis central air supply system to provide a flow of 750 lbs/sec will permit testing the modern turbojet and medium size turbofan engines not possible with the lower air supply. It will also increase the margin of flexibility for smaller engines. By contrast, the air flow capacity available at the AEDC and industry facilities is over 1200 lbs/sec. This complex is NASA's only capability in this area of aero propulsion research and serious consideration must be given to upgrading its capabilities or allowing it to phase out over the next decade and rely strictly on DOD's and the industry's capabilities.

c. Components:

The balance of the Lewis component facilities falls within a wide range of capabilities and cannot be easily classified as U.S. Class or just NASA Class, i.e., important only to Lewis' in-house research effort. A recent survey and assessment of these facilities was undertaken by a NASA senior management team and a separate report on their findings is available. No further analysis or recommendations on any of these facilities will be made in this report.

TABLE XVIII

NASA AIRBREATHING PROPULSION FACILITIES

LEWIS FACILITY	PREMIER CLASS	YEAR BUILT	REPLACE. COST ($M)	YEAR UPGRADED	OPERATIONS # SHIFTS	COMMENTS
WIND TUNNELS						
- 10X10 Ft.	***	1955	70	--	6/Wk.	Supersonic - Hi Mach #
- 9X15 Ft.	**	1968	9	--	4/Wk.	Subsonic - No Engine Burns
- 8X6 Ft.	**	1948	66	--	6/Wk.	Subsonic/Supersonic - Low End
	AVG:	1957	$145M			
ENGINE TEST FAC.						
- PSL-1		1950	50	1976	Standby	May be Reactivated Within 18 Mo.
- PSL-2		1950	50	1966	Standby	
- PSL-3	**	1972	60		2/Day	Air Mass Flow Inadequate for Large Turbofans but Excellent Res. Facility for Urbojets & Small Turbofans. Needs Some Upgrades
- PSL-4	**	1972	60		2/Day	
	AVG:	1961	$220M			
COMPONENT FACILTIES						
TURBINES:						
- Heat Transfer		1979	(1)	1983	1/Wk.	
- Hot Cascade		1986	(4)	--	Oper. 1986	New Unique Facility for Small Engines
- HPF	***	1980	(15)	--	Standby	Unique "Hot Section" Testing Facility
- Large Warm		1965	(5)	1979	Standby	
	AVG:	1971	(27)			
COMPRESSORS:						
- Lge Low Speed Centrifugal	***	1986	(4)		Oper. 1986	Unique Large for Internal Flow Measurements & Res.
- Transonic Oscil. Cascade		1980	(1.5)		1/Day	
- Multi-Stage Axial Flow		1970	(5)		1/Day	
- Small Multistage		1971	(3)	1986		
- Small Centrifugal		1983	(2)		1/Day	
- Sm. Single Stage Centrifugal		1970	(1)		Standby	
- Single Stage Axial		1970	(3.5)		1/Day	
- CoaxiaL Jet		1971	(1.5)	1977	Standby	
	AVG:	1975	(21.5)			

TABLE XVIII CONT'D

LEWIS FACILITY	PREMIER CLASS	YEAR BUILT	REPLACE. COST ($M)	YEAR UPGRADED	OPERATIONS # SHIFTS	COMMENTS
COMPONENT FACILITIES						
COMBUSTORS:						
- Low Pressure		1974	(2)		Standby	
- Medium Pressure		1971	(7)	1980	2/Wk.	
- High Pressure		1979	(15)		Standby	
		1975	(24)			
FAN COMPONENTS:						
- Fan Acoustic		1975	(3.5)		Standby	
COMPONENTS TOTAL:	AVG:	1974	(76)			
ENGINE RESEARCH BLDG.						
- Air Supply & Various Small Test Cells			250			
AIRBREATHING PROPULSION TOTAL	AVG:	1970	$690M			

( ) Designates Approximate Value of Individual Test Cell Equipment & Hardware. Does Not Include Any Portion of Engine Research Building Structure or Supporting Systems.

4.2.1 AIRBREATHING PROPULSION FACILITIES SUMMARY

Of the Lewis inventory of aero propulsion facilities, only four are considered unique or capable enough to be rated as World Class facilities, although this is a very conservative judgement, particularly with respect to the PSL complex. The average age of all the facilities listed in Table XX is about 15 years (excluding those under construction), but the large wind tunnels and engine test facilities are over 20 years old. Fifteen or 20 years ago NASA was in the forefront of aero propulsion technology and facilities. Now, however, they have lost this preeminence to DOD and industry across the full spectrum of airbreathing propulsion facilities, particularly in the category of large test and development facilities. Nevertheless, the Lewis facilities are still very good fundamental research and applications tools, which, as indicated previously, when combined with its overall expertise, are in high demand by the industry and DOD. This is particularly true for the fundamental research facilities which the latter generally lack. To maintain even this small edge, however, serious attention must be given to the improvements indicated above.

4.3 FLIGHT SIMULATORS

There are 11 flight simulation facilities in NASA meeting the R&D criterion established for this assessment, with a replacement value of approximately $85 M. These simulators are about evenly divided between Ames and Langley, with the latter owning the most expensive (TRSV aircraft at $36 M). These are relatively new facilities of about 1977 average vintage. However, as indicated earlier in this report, this is a rapidly changing technology area and subject to obsolescence after 5 to 10 years. Table XIX contains the pertinent information on this group of facilities.

a. World Class Simulators:

ARC: Advanced Concepts Simulator: This generic flight deck simulator is part of Ames' new Man-Vehicle System Research Facility (MVSRF), and one of three such facilities in the U.S. (Langley and Lockheed-GA own the others). It is now in the forefront of this technology and other than the addition of an "intelligent cockpit simulator" will not need any other major modifications in the near future, but is certain to require general upgrading before the year 2000.

ARC: Vertical Motion Simulator (VMS): This is one of the world's largest and most unique motion simulators, and therefore one of the busiest. It is currently being upgraded with a state-of-the-art Advanced Cab and Visual System (ACAVS) to provide CGI dome projection capability plus highly modular rotorcraft -- specific flight deck simulation.

LRC: Transport Systems Research Vehicle (TSRV): This Boeing 737 airborne simulator is uniquely instrumented to study a wide array of flight management related technology and procedures in an air traffic control (ATC) environment. It is being upgraded to extend its viability over the next decade as a state-of-the-art research tool. However, a decision will have to be made before the year 2000 on whether to replace the aircraft or phase out this NASA capability.

LRC: Mission Oriented Terminal Area Simulation (MOTAS): The MOTAS is a ground-based facility in which flight management and flight operations research can be conducted in a highly realistic environment. This facility is very flexible and can be adapted to various aircraft, terminal area, and ground control configurations. It is a new facility (1983) and still in an evolutionary state. Integration with other Langley simulators, such as the General Aviation and DC-9 simulators, plus the Advanced Concept facility, are being planned. No other major upgradings are contemplated at this time, but there are certain to be some evolutionary changes within the next 10 to 15 years.

LRC: Advanced Concepts Simulator: This advanced cockpit simulator is now coming on-line at Langley with the latest state-of-the-art equipment. It is similar in nature to the Ames and Lockheed facilities, except that the Ames simulator is used for human factors research (pilot/instrument interaction), while the Langley facility is used for flight management research (i.e., flight controls, instruments, and displays as they affect the pilot and vehicle in an air traffic control environment). The Lockheed facility is oriented toward developing specific aircraft cockpit configurations and hardware. Other than the addition of external visual capability when WAVES becomes operational, no other modifications are contemplated.

b. U.S. Class Simulators:

ARC: Flight Simulator for Advanced Aircraft (FSAA): This large moving base simulator is one of the oldest in NASA and in serious need of upgrading with new servo controls and modern computer generated imagery systems. Although lacking the large amplitude, vertical motion capability of the VMS, it provides very large lateral motion capability; a very desirable feature for CTOL aircraft simulation. An upgraded FSAA would also off-load the VMS's heavy schedule. The FSAA is currently on standby status and must be upgraded soon unless it is determined that this capability is not needed for the aircraft technology programs of the future.

c. NASA Class Simulators:

ARC: Boeing 727 Flight Simulator: Although a modern replica of a B-727 cockpit, this flight deck simulator is not unique in the world or the U.S.. However, it is a good complementary capability to the Advanced Concepts cockpit; both of which are elements of the MVSRF. No major alterations to this flight deck simulator are contemplated in the foreseeable future.

LRC: Differential Maneuvering Simulator (DMS): This facility is one of the oldest simulators at Langley and in need of upgrading to bring it to World Class or U.S. Class caliber once again. A high angle-of-attack capability is planned for the near future.

LRC: DC-9 Full Work Load Simulator: As with the Ames 727 cockpit simulator, this is another vehicle specific flight deck which is not unique in the U.S.. Both of these decks have been included in this assessment because they are used more for research than are their industrial counterparts, most of which are trainers. This is a recent addition to Langley's simulation capabilities and will not need significant modifications in the foreseeable future.

4.3.1 FLIGHT SIMULATORS SUMMARY

Of the 11 major flight simulators owned by NASA, 5 are considered World Class facilities and 2 more could be returned to that status with some rehabilitation or upgrading. These 2 are the FSAA at Ames and DMS at Langley, both about 15 years old. NASA's strength in this field is in its large motion systems and advanced research cockpits. However, one could question whether the future direction in this field will involve the need for the large motion cues offered by the Ames facilities, or whether visual and other sensory cues will replace the need for the large hardware of a VMS. Even so, the technologies (computers and electronics) that dominate this field are advancing rapidly, making these facilities obsolete within a very short period unless continually upgraded.

There is also a trend to consolidate the various types of simulation capabilities existing within each installation (NASA Center) into a "simulation complex" whose constituent motion and/or visual hardware are driven by a central, powerful computer. In this manner even the smaller "rigs" have access to powerful image generators or sophisticated algorithms, and the need for replicating large and expensive central processing units (CPU's) is obviated. In this context, urgent attention must be given to the Ames EDP systems currently supporting their simulator complex. Some of these CPU's are over 15 years old and in critical need of replacement. The cost of this replacement will probably be recouped in a very short time through maintenance savings and increased productivity, in addition to the gains obtained in simulation capacity.

TABLE XIX

NASA FLIGHT SIMULATORS

FACILITY	PREMIER CLASS	YEAR BUILT	REPLACE. COST ($M)	YEAR(S) UPGRADED	OPERATIONS # SHIFTS	COMMENTS
AMES						
B-727 Flt. Sim.	*	1983	5	--		Not Unique Facility in U.S.
Adv. Concepts	***	1984	6	--		
FSAA	**	1969	6	--	Standby	Needs Major Rehab.
VMS	***	1979	10	1982	2/Day	
6 Degrees of Freedom	--	1963	4	1984	--	Down For Upgrading Oper. in 1985
5	AVG:	1976	$31M			
LRC						
TSRV	***	1973	36	1984		
DMS	*	1971	8	1976		Needs Upgrading for High-Capability
DC-9 Simulator	*	1983	4	--		
Visual Motion	--	1971	1	74/76		Needs Replacing
MOTAS	***	1983	1			
Adv. Concepts	***	1984	4			
6	AVG:	1977	$54M			
11		1977	$84M			

5. CONCLUSIONS AND RECOMMENDATIONS

5.0 GENERAL FINDINGS

Based on the information obtained from this survey, the United States' strength in aeronautical facilities is unmatched by any single nation or combination of nations in the free world. This is true across the entire spectrum of facilities, whether used for fundamental research or development purposes. The Europeans' best capabilities reside in their wind tunnels, particularly in their modern facilities. The Japanese strength is evolving in the flight simulation area. Within the U.S., NASA is the leader in overall wind tunnel capabilities, DOD and industry have the best and largest airbreathing propulsion facilities, while the industry and NASA share the lead in R&D flight simulators. This lead, however, can be transitory, particularly in the rapidly evolving area of flight simulators where technological obsolescence can be reached within 5 to 10 years. Even the large steel and mortar facilities like wind tunnels and engine test facilities do reach the end of their useful life and/or become obsolete. Some of the Nation's premier facilities are now facing such a point; particularly at NASA where the average wind tunnel is about 30 years old. In contrast, the Europeans are building newer, more modern facilities (wind tunnels), as are the Japanese (simulators and computational facilities).

Some specific observations are as follows:

- Wind Tunnels: The U.S. owns the greatest number, the largest size, best Reynolds number, and broadest Mach number range wind tunnel capabilities across all speed regimes. The Europeans own some excellent modern facilities that offer high productivity and flow characteristics such as the Dutch DNW, French F-1, and British 5-meter tunnels. NASA owns the largest wind tunnels (40x80x120 ft. complex), the highest Reynolds number transonic capability (NTF), and best set of hypersonic tunnels (Ames' 3.5 ft. and Langley's hypersonic complex). A European consortium is scheduled to build a high Reynolds number facility like the NTF, but it is still 5 to 10 years in the future. NASA's planned Altitude Wind Tunnel (AWT) will fill a critical gap in aero propulsion and icing research, but it too is about five years in the future.

- Airbreathing Propulsion Facilities: The U.S. is distinctly the leader in this category of facilities. In propulsion wind tunnels the DOD, through AEDC's 16S and 16T tunnels, and NASA, through Lewis' 10x10 and 8x6 ft. tunnels, are the leaders. In engine altitude test facilities, the DOD has the best overall facility in AEDC's modern Aeropropulsion System Test Facility (ASTF). The U.S. industry is also very well equipped with a variety of facilities covering the entire spectrum of engine test capabilities, where General Electric and Pratt & Whitney are the leaders. In propulsion components, the U.S. industry is also the leader with the most comprehensive set of facilities. NASA also offers some unique and outstanding capabilities in this area of propulsions research. The foreign capabilities are concentrated mostly in engine test facilities at the U.K.'s RAE/Pyestock (formerly NGTE) Center and France's CEPr at Saclay. Some notable wind tunnel propulsion capabilities also exist in Canada's 10x20 NRC tunnel, France's S1 tunnel at Modane, and the Netherlands' DNW complex.

- Flight Simulators: Although this survey did not yield as much information on this category of facilities from foreign sources, it is the general opinion that the U.S. is significantly in front of its European counterparts, although some excellent capabilities are being developed in West Germany and Japan. The premier U.S. capability exists in industry and NASA. The latter owns the World Class facilities in motion simulators and some generic R&D flight decks, while the industry has excellent capabilities across all categories of simulation facilities.

5.1 NASA FACILITIES

Of the 72 major NASA aeronautical facilities included in this survey, with a current replacement value of over $2 billion, 27 (18 wind tunnels, 4 propulsion, and 5 flight simulation facilities) are considered World Class and 12 are at least of national importance. This combined capability makes NASA a major force in the Nation's current standing as the Western World's leader in aeronautical R&D. However, as indicated previously, there are some gaps in this aggregate capability and the existing facilities are becoming obsolete (particularly the wind tunnels, which are also NASA's principal strength).

5.1.1 WIND TUNNELS

As a group, NASA's wind tunnels offer a broader range of size and overall capabilities than any other owner or class of owner (DOD, industry, academia), foreign or domestic. If there are any gaps in its total research/test envelope it is in the ability to test large scale propulsion/airframe systems such as turboprops and V/STOL at properly simulated speed, temperature, and altitude conditions. Another void is the absence of a reasonable size supersonic wind tunnel providing good laminar flow, low turbulence conditions for performing research on low drag air foil and fuselage designs for future supersonic cruise transports. These are capabilities currently unavailable anywhere in the Western World. Just as important as filling these gaps, however, is preserving the capabilities NASA has. As discussed repeatedly in this report, there are some premier facilities that unless rehabilitated will soon lose their preeminent position and become possible embarrassments rather than showpieces. The following reiterates the most pressing needs over the next 5 to 10 years:

- General rehabilitation/modernization of the supersonic Unitary Plan wind tunnels at Ames.

- Overhaul of the 12 ft. pressure tunnel at Ames to maintain its high pressure, high Reynolds number capability and improve its productivity.

- Rehabilitation and upgrade of Lewis' 10x10 and 8x6 ft. propulsion wind tunnels.

- General overhaul of Langley's hypersonic capabilities.

- Acquisition of a large, airframe/propulsion integration facility with altitude simulation capabilities.

- Modifications to or acquisition of a supersonic wind tunnel with good laminar flow features.

5.1.2 AIRBREATHING PROPULSION

In airbreathing propulsion, NASA's facilities offer good research capabilities but not of the caliber or preeminence of its wind tunnels. As stated above, the Nation's premier capabilities reside in industry and the DOD, certainly for development testing. NASA's strength is in its research role in aero propulsion, and, except for the needs indicated earlier and reiterated below, this role is adequately served by its propulsion wind tunnels, engine and component research facilities. However, the same problems of aging and obsolescence plague these facilities as they do the wind tunnels, and some rehabilitation and modernization just to maintain their current capabilities are necessary. The most pressing needs appear to be:

- General rehabilitation of the 8x6 ft. wind tunnel.

- Upgrading of the PSL air supply system to provide air flow capacity just above the marginal levels now available. Also modifications to permit testing at sea level conditions.

- Maintaining the High Pressure, Hot Section Facility (HPF) in a ready status and at full capability.

- Acquiring a large scale turbine research capability.

The last two items underscore the importance of NASA's fundamental research capability in this area. Although industry and the DOD are well equipped to perform the necessary development testing on their facilities, they all look to NASA for the more basic and problem-solving type of investigations. Internal computational fluid mechanics (ICFM) is an example where NASA must take the lead; not only through sophisticated computational tools, but also through the appropriate facilities by which computational models can be verified.

5.1.3 FLIGHT SIMULATORS

Although NASA's capabilities cover the entire spectrum of R&D flight simulators, its premier facilities are its large moving base simulators at Ames and the advanced, generic cockpit simulators at Ames and Langley. However, rapid obsolescene is the principal nemesis of these facilities and world preeminence can be maintained only through continuous upgrading. The advanced cockpit simulators are new, state-of-the-art facilities, but the large motion simulators at Ames are older and due for some rehabilitation and upgrading soon. Given the rapid advancement of this technology, it may be necessary to consider whether these large, costly facilities will still be required by the year 2000, or whether alternative methods of providing some motion and/or visual cues to the pilot will be available (and sufficient) through other mechanical or electronic means. If not, the Ames FSAA is already overdue for some extensive upgrading, and the VMS also may need upgrading within the next 10 to 15 years.

5.2 FACILITIES LONG RANGE PLANNING

5.2.1 BUILDING NEW CAPABILITIES

The conclusion has been drawn from the foregoing that the U.S. is the current leader in aeronautical facilities throughout the free world. It can also be concluded that except for meeting some new challenges in civil and military aviation projected for the 21st century, the U.S., as a whole, is quite well facilitized. Those challenges for which new or additional capabilities are needed include: supersonic cruise transports, low-hypersonic military vehicles (fighters and missiles), high-hypersonic transatmospheric vehicles, all weather rotorcraft, or V/STOL aircraft. To meet these challenges some new capabilities already cited or alluded to in the body of this report will be required. These are a mixture of both "test" as well as "research" capabilities, with the former requiring mostly large expensive facilities and the latter needing only relative modest investments. The more obvious ones are:

- Large scale, high Mach number hypersonic aerodynamic and thermal structures facility (wind tunnel)

- Low noise, low turbulence supersonic wind tunnel large enough to test detailed model configurations (4 ft. test section minimum)

- Large scale airframe/propulsion integration wind tunnel with true altitude simulation

- Large scale hypersonic propulsion test facility.

Other needs to satisfy the technology requirements of the next century can be gleaned from the Aero 2000 study and report referenced earlier. Deciding or recommending where these facilities should be built (industry, DOD, or NASA) is beyond the purview of this report and a subject for much discussion among all the principals concerned. However, some observations (even if obvious) that may influence such decisions are in order:

- Industry is generally in no financial position to underwrite the large capital investment required of the large test facilities unless there is an immediate market from which to recover these investments. Although the term industry is used here collectively, it actually signifies individual companies concerned about their individual products and survival, and generally unlikely to pool their resources to build common facilities (antitrust laws notwithstanding). Where the payoff is significantly downstream, as in most of the above examples, it is very unlikely that the industry will volunteer to build these facilities, and the task will be left to the Federal Government.

- The DOD owns an extensive set of facilities ranging from the fundamental research to development type. Should any of the above facility candidates be built by DOD, it is very likely that AEDC would be the location. As such, the facility will probably be used principally for development test purposes rather than for research. In fact, if current practice is any indication, research activities may have difficulty competing for time on these facilities, or be priced out altogether from what are relatively high user fees.

- If fundamental or applied research is to be the principal thrust of the above facilities, history and current practice would support NASA as a better suited owner/operator than the AEDC.

Irrespective of where these facilities are to be built or by whom, a coordinated process must be followed in arriving at these decisions, since it is the country as a whole that has the biggest stake. NASA is currently examining the output from this survey and the Aero 2000 activity to determine in more detail than expressed above, what are the new capabilities required to support the technology needs of the next century. Expanding existing capabilities as well as new facilities are being considered. This "Long Range Facilities Plan" will focus mainly on the large (greater than $25 million) budget busters that must be programmed for and properly coordinated and advocated before they can be successfully budgeted. DOD is proceeding with a parallel effort to identify these needs from their perspective, and a totally coordinated "plan" is projected by the end of 1985. The NASA planning process will, of course, involve the usual coordination and advice from the aviation industry and various standing advisory groups before this "plan" is finalized.

5.2.2 MAINTAINING EXISTING CAPABILITIES

Other than examining existing capabilities as possible candidates for expansion/upgrading to meet some of the new requirements discussed previously, a serious review must be undertaken to determine which of those facilities in the total U.S. inventory (not just NASA's) must be rehabilitated just to maintain their current capabilities. As already indicated in this report, the majority of the U.S. wind tunnels are approximately 25 to 30 years old and will be around 40 years old by the year 2000. As also indicated, the U.S. tunnels are already more antiquated than many of the European facilities and in need of upgrading. Using the results of this survey and assessment as a reference point, NASA is designing a strategy for addressing the anticipated needs of its aging facilities and incorporating them into their Facilities Long Range Plan (LRP). This strategy will be based on the following:

- Identifying only major rehabilitation efforts anticipated to cost over $10 million each.

- Giving first priority to NASA's World Class facilities, as assets that the U.S. must protect to retain its world leadership in this area.

- Determining those national facilities (U.S. Class) that will continue to be important assets to the Nation and to NASA.

- Evaluating NASA's fundamental research or "backyard" facilities on a periodic basis to determine their continuing value to NASA's R&T programs.

The latter will most likely fall outside the $10 million criterion and rarely be included in the LRP. These as well as the more minor repairs and rehabilitations will be covered in the annual budget process, wherein more consideration (and scrutiny) can be given to small projects and to ad hoc needs requiring immediate attention.

It is understood that the DOD is also addressing this matter in their parallel effort and will be part of the "coordinated plan" between the two agencies. In the case of industry's facilities, while part of the total U.S. inventory, the decision to maintain or to scrap them is generally based on financial considerations rather than on their value to the country. As such, they cannot be incorporated into any coordinated plan, other than the effect their elimination from the national inventory may have on NASA or DOD decisions concerning their own facilities.

5.2.3 DEACTIVATION OF EXISTING FACILITIES

Whenever the subject of constructing new facilities or rehabilitating old ones is discussed, the question of deactivating the old ones surfaces. This is a controversial issue which can draw convincing arguments from either side. On the one hand, it seems reasonable to expect that as larger and better facilities are built, those with older or lesser capabilities can be retired so that the number of facilities in operation need not continue to proliferate. On the other side is the argument that a newer, larger facility does not necessarily displace an older, smaller one, since the former, in all likelihood, will be in high demand by high priority research or development projects, leaving the fundamental researcher waiting at the end of a long line with little likelihood of using the new facility. Moreover, the larger facilities may offer more than the researcher needs at a considerably higher operating cost. The researcher has no alternative but to stay with the smaller or less capable facility to pursue his fundamental works. The net result is usually a tendency to keep both facilities unless the older one is clearly inferior or unusable.

History indicates that facilities are deactivated for one of the following principal reasons:

1. Lack of use; no program needs
2. Serious breakdown not worth repairing
3. Facility replaced with newer one
4. Lack of operating funds or too costly

Deactivated facilities are subsequently disposed of or placed in one of several statuses:

1. Standby: Nonoperational but maintained in working order
2. Mothballed: Preserved but not maintained
3. Surplused: Available for use elsewhere
4. Dismantled: Inoperable, equipment gutted, but basic structure in place
5. Demolished: Scrapped and removed

Experience also indicates that decisions to shut down facilities are not normally the result of a long range planning process, but rather made ad hoc for one of the above reasons, which, over time, act as an effective mechanism for periodically thinning out the facility ranks.

A review of NASA's recent history discloses that over the 14-year period between 1970 and 1984, about 70 medium and small aeronautical facilities were deactivated, of which 90% were for programmatic reasons and the other 10% because of age. Only 20% were then placed on standby and about 70% were dismantled or demolished, consistent with the judgement that the program needs had disappeared and no further use for these facilities was projected. These statistics support the belief that a "natural selection" process is effectively controlling the proliferation or needless retention of the smaller facilities.

The very large National or World Class facilities present a different situation, since the same "natural selection" process reflected above does not operate on them. The reasons are obvious:

- Because of their importance and size they receive constant scrutiny and attention. They neither proliferate nor waste away unnoticed.

- Because of their broad range of capabilities and use, program demands do not normally disappear overnight, if at all. Their program base is usually very large. Furthermore, once in place, these facilities become natural magnets for people and research ideas, thereby driving programs rather than the other way around; in effect perpetuating their own existence.

- Their importance usually grants them top priority for upgrading and rehabilitation. Eliminating these facilities because of age, breakdowns, or obsolescence becomes a very deliberate and involved decision, one which is seldom projected very far into the future.

For these large facilities the decision to retain or deactivate is principally based on anticipated future needs -- at least for government R&D facilities. But since this vision is generally myopic, the capital investment is large, and there is always the optimism that upgradings and rehabilitation to stem obsolescence are possible, there is a general reluctance to take that irreversible step until time itself becomes the deciding factor. This is not to imply that the large facilities are immune from deactivation, but that preparing a long range plan for this eventuality is extremely difficult if not impossible, and in any event probably indefensible.

The situation in industry is somewhat different since, as expected, the principal consideration is a financial one, particularly in product development. For these types of facilities the development/production schedule usually dictates the lifetime of a particular facility and its approximate deactivation time frame. On the other hand, for their more generic application or basic research facilities and laboratories, industry's situation is probably very similar to that of the Federal laboratories and encounters the same difficulties in preparing long range facility deactivation plans.

In summary:

- There exists an unstructured, but yet effective natural selection process for weeding out medium and small facilities.

- The large facilities receive sufficient scrutiny through a more formal decision-making process.

- Deactivation decisions are usually made because of programmatic/funding reasons, although more so for the smaller than the larger facilities.

- These decisions are usually ad hoc and near term rather than through long range planning.

- Industry decisions are principally based on financial/product considerations rather than long term national needs. These are left up to government laboratories. Decisions on basic research facilities are probably no different than for government laboratories.

- Tying facilities deactivation to facilities long range plans can be useful only where replacement facilities in the long range plan are involved. In such instances, full coordination across all government agencies is necessary.

5.2.4 TEST FACILITIES VERSUS NUMERICAL SIMULATION

Another issue that must be addressed whenever the subject of facilities long range planning is discussed is whether large test facilities will continue to play an essential role in future aircraft development, or whether the science (art) of numerical simulation will make these test facilities unnecessary.

Assuming the continued rapid progress anticipated in the science of simulation, aided by the ultra fast, high capacity computers and their sophisticated software, it is still considered very doubtful that this level of sophistication will reach the point by the year 2000 where accurate simulation of external flows over complex shapes will be possible. Even less probable is the accurate simulation of internal flows through complex turbofan/turbojet engines. As such, the need for large wind tunnels and engine test facilities over this time frame is not seriously threatened by numerical simulation facilities.

The longer range effect is another matter. Simple extrapolation based on current developments plus a generous measure of optimism leads to a conclusion that these new techniques will become a powerful force in future engine and aircraft designs and development. This is an important consideration, since the large and expensive test facilities that may be proposed and built to meet the technology challenges facing the 21st century could be around for 30 to 40 years if past history is any indication. Decisions on whether to build these facilities will have to depend heavily on the anticipated capabilities of simulators such as the Numerical Aerodynamic Simulation (NAS) facility at Ames.

The current thinking into the next 15 to 25 years leans in the following direction:

- Numerical simulation techniques and facilities will be used to perform much of the initial engineering design of future vehicle configurations, and to perform many of the necessary iterations to accommodate options or changes to aerodynamic configurations, etc., before test models are built. Much of the trial and error iterations now performed in wind tunnels with repeated alterations to expensive models will be avoided.

- Large test facilities will be used to check out large or full scale prototypes before flight tests. Considering the high risk in lives and very expensive flight hardware, it is doubtful that this vital step in the development and flight test sequence will ever be completely eliminated, nor the corresponding test facilities.

- Lastly, there will also be a continuing need for the basic research facilities where the fundamental laws and behavior can be investigated and translated into the algorithms used by the simulators. This code development/verification relationship between the small facilities or laboratories and numerical simulators will probably continue until a substantial data base is gathered.

Figure 18 summarizes the above relationships graphically, highlighting the centerpiece role of numerical simulators with respect to research and test facilities. The opinion is that numerical simulation techniques will replace the more commonplace facilities (mid-size wind tunnels) rather than the smaller or larger ones. This has a crucial implication for the majority of wind tunnels in existence today and the need for retaining them into the next century.

FUTURE ROLE OF AERONAUTICAL FACILITIES

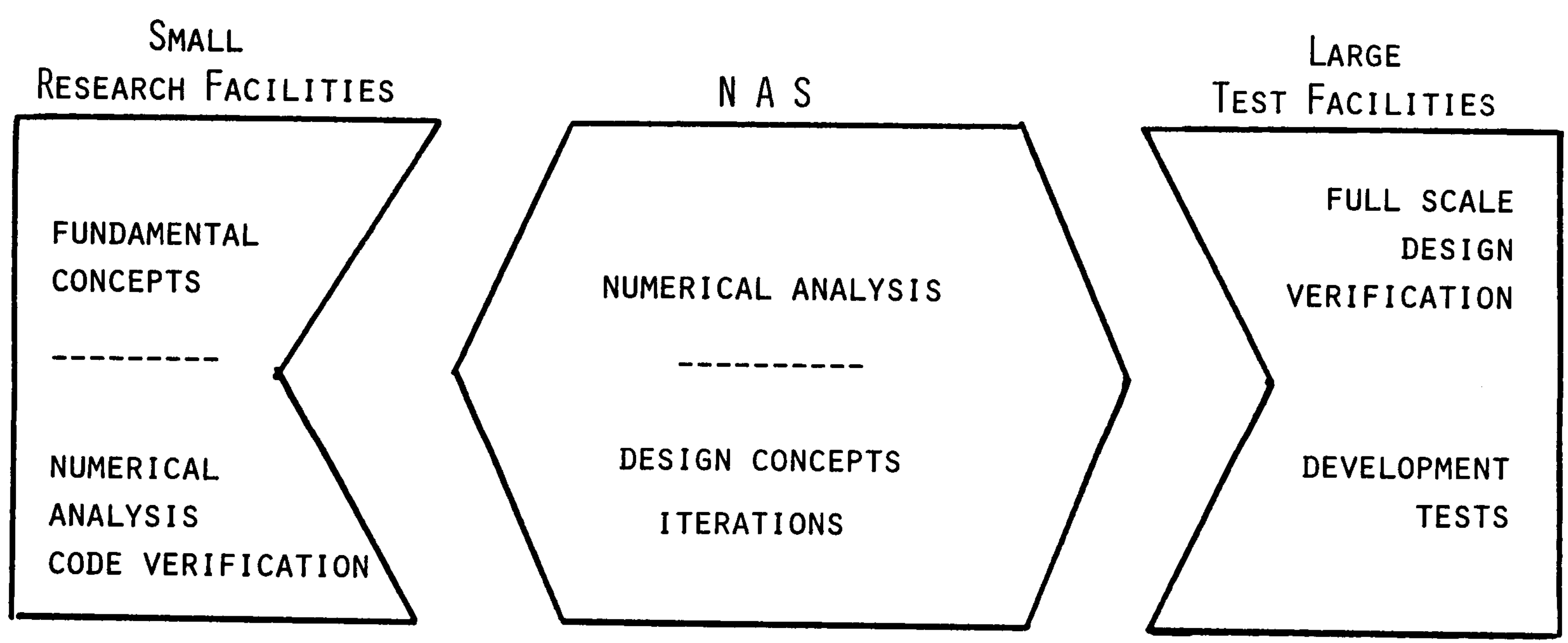

Figure 18

APPENDIX

A

APPENDIX A

CROSS-INDEX BY INSTALLATION

U.S. GOVERNMENT INSTALLATIONS

Location and Facility Description	Test Section (ft)	Speed Range (Mach No.)	Reynolds Number (per ft x 10^{-6})	Comments
U.S.-NASA				
Ames Research Center				
Subsonic Wind Tunnels				
80 x 120-ft	80 x 120	100 mph	0 - 1	High R_e, Propulsion
40 x 80-ft	40 x 80	300 mph	0 - 3	High R_e
12-ft Pressure Tunnel	11.3 dia	0.6	0 - 9	High R_e, Pressurized
7 x 10-ft (1)	7 x 10	0 - 0.33	0 - 2.6	V/STOL
7 x 10-ft (2) Army	7 x 10	0.33	0 - 2.6	Rotorcraft, Army Facility
Transonic Wind Tunnels				
14-ft	13.5 x 13.71	0.5 - 1.2	2.6 - 4.2	Standby
11-ft (Unitary)	11 x 11	0.4 - 1.4	1.26 - 9.4	
2 x 2-ft	2 x 2	0.2 - 1.4	0.5 - 8.7	
Supersonic Wind Tunnels				
9 x 7-ft (Unitary)	9 x 7	1.55 - 2.5	0.8 - 6.5	Captive Trajectory
8 x 7-ft (Unitary)	8 x 7	2.4 - 3.5	0.6 - 5.0	Captive Trajectory
6 x 6-ft	6 x 6	0.25 - 2.2	0.5 - 5.0	
Hypersonic Wind Tunnels				
3.5-ft Hypersonic	3.5 dia	5, 7, 10 Nominal	0.3 - 7.4	Standby
Langley Research Center				
Subsonic Wind Tunnels				
30 x 60-ft	30 x 60	38 - 132 ft/sec	1	Open Throat
4 x 7-m	14.5 x 21.8	318 ft/sec	2.1	Moving Ground, V/STOL
7 x 10-ft	6.6 x 9.6	0.2 - 0.9	0.1 - 3.2	
Low-Turbulence Pressure (LTPT)	7.5 x 3	0.05 - 0.5	0.1 - 15	2-D, Pressurized
Vertical Spin Tunnel	20 dia, 25 H	132 ft/sec	0.6	Vertical Spin

U.S. GOVERNMENT INSTALLATIONS

Location and Facility Description	Test Section (ft)	Speed Range (Mach No.)	Reynolds Number (per ft x 10^{-6})	Comments
Langley Research Center				
Transonic Wind Tunnels				
16-ft	15.5 x 15.5	0.2 - 1.3	1.2 - 4.2	Propulsion Integration
8-ft	7.1 x 7.1	0.2 - 1.4	0.1 - 6	Pressurized
0.3-m 2-D Test Section	8 x 24-in	0.2 - 0.9	120	Cryogenic
0.3-m Flex Wall Test Section	13 x 13-in	0.2 - 1.1	120	Cryogenic
6 x 28-in	6 x 28-in	0.2 - 1.2	4.0 - 25	2-D
NTF	8.2 x 8.2	0.2 - 1.2	145	Cryogenic, Pressurized
Transonic Dynamics Tunnel (TDT)	16 x 16	0 - 1.2	2.8 Air; 8.5 Freon	Flutter
Supersonic Wind Tunnels				
Unitary Tunnel	#1 4 x 4	1.47 - 2.86	0.5 - 12.2	
	#2 4 x 4	2.29 - 4.63	0.5 - 9.5	
Hypersonic Wind Tunnels				
8-ft HTT	8 dia	4 - 7.2	0.3 - 2.2	Thermal Structures
20-in Mach 6	20 x 20.5	6	0.5 - 10.5	
CF_4	20-in dia	6	0.3 - 0.5	
Continuous Flow	31 x 31-in	10	0.4 - 2.4	
Hypersonic Helium Tunnel	22-in dia	17.6 - 22.2	1.1 - 11.3	Aerodynamic Leg
	22 or 36-in	20 or 40	1.3 - 6.0	Fluid Mech. Leg
Hypersonic Nitrogen	6-in dia	18	0.17 - 0.40	
Mach 20 High R_e Helium	5 dia	16.5 - 18	1.9 - 15	
Mach 8 Variable Density Tunnel	18-in dia	8	0.1 - 12.0	
Mach 6 High R_e Tunnel	12-in dia	6	1.8 - 50	High R_e Blowdown
Scramjet	4 dia	4.7 - 6.0	0.13 - 5.2	Propulsion
Lewis Research Center				
Subsonic Wind Tunnels				
9 x 15-ft	9 x 15	0 - 0.2	0 - 1.4	Propulsion
AWT (Proposed)	20 dia x 56 L	0.9	3.5	Icing, Propulsion, No Data Sheet
IRT	6 x 9	0 - 0.5	3.3	Icing

U.S. GOVERNMENT INSTALLATIONS

Location and Facility Description	Test Section (ft)	Speed Range (Mach No.)	Reynolds Number (per ft x 10^{-6})	Comments
Lewis Research Center				
Supersonic Wind Tunnels				
10 x 10-ft	Closed 10 x 10	2 - 3.5	0.12 - 3.4	Propulsion
	Open 10 x 10	2 - 3.5	2.1 - 2.7	
8 x 6-ft	8 x 6	0.4 - 2	3.6 - 4.8	Propulsion
1 x 1-ft	12 x 12-in	1.6 - 5.0	1.5 - 36	Internal Fluid Dynamics
Marshall Space Flight Center				
Transonic Wind Tunnels				
High Reynolds Number	32-in dia	0.3 - 3.50	7 - 200	2-D, High R_e, Pressurized
U.S. DOD				
Arnold Engineering Development Center				
Transonic Wind Tunnels				
16T	16 x 16	0 - 1.6	0.1 - 6.0	Propulsion, Flutter
4T	4 x 4	0.1 - 1.3, 1.6	2.0 - 6.5 @ M=1.6	Captive Trajectory
		2.0	1.3 - 6.1 @ M=2.0	Supersonic
Supersonic Wind Tunnels				
16S	16 x 16	1.5 - 4.75	0.1 - 2.6	Propulsion
APTU	16 dia	0 - 4.5	–	Propulsion, Ramjet
von Karman A	3 x 3	1.5 - 6	0.3 - 9.2	Captive Trajectory
Hypersonic Wind Tunnels				
von Karman B	50-in dia	6 or 8	0.3 - 4.7	Captive Trajectory
von Karman C	25 & 50-in dia	4, 10	0.4 - 1.3 @ M=4	Aerothermal, Captive
			0.3 - 4.7 @ M=10	Trajectory
David Taylor Naval Ship R&D Center				
Subsonic Wind Tunnels				
8 x 10-ft	8 x 10	30 - 275 ft/sec	0 - 1.77	Flutter
Transonic Wind Tunnels				
7 x 10-ft	7 x 10	0.25 - 1.17	1 - 5	Captive Trajectory

U.S. GOVERNMENT INSTALLATIONS

Location and Facility Description	Test Section (ft)	Speed Range (Mach No.)	Reynolds Number (per ft x 10^{-6})	Comments
Naval Surface Weapons Center				
Supersonic Wind Tunnels				
Boundary Layer Channel	12 x 12-in	3 - 5	2 - 24	Vertical Test Section
Supersonic #2	16 x 16-in	0.3 - 5	0.5 - 21	Open Jet
Hypersonic Wind Tunnels				
Hypersonic #8	17 - 22-in dia	5 - 8	0.6 - 50	
Hypersonic #8A	24-in dia	18	0.2 - 0.6	
Hypersonic #9	5 dia	10, 14.5	0.06 - 20	
Wright Aeronautical Laboratories				
Subsonic Wind Tunnels				
Vertical Tunnel	12 x 15	0 - 150	0 - 0.91	
Supersonic Wind Tunnels				
Mach 3 High R_e	8.2 x 8-in'	3	10 - 100	High R_e
Hypersonic Wind Tunnels				
20-in	20-in dia	12, 14	0.4 - 1.0	
Mach 6 High R_e	20-in dia, 20-in L	6	10 - 30	High R_e

U.S. INDUSTRY

Location and Facility Description	Test Section (ft)	Speed Range (Mach No.)	Reynolds Number (per ft x 10^{-6})	Comments
Boeing Vertol				
Subsonic Wind Tunnels				
20 x 20-ft V/STOL	20 x 20	0.325	0 - 2.3	Rotorcraft
Boeing-Seattle				
Subsonic Wind Tunnels				
9 x 9-ft	9 x 9	0.36	2	Propulsion
Low Speed Research	8 x 5	0.18	1.2	
Transonic Wind Tunnels				
Transonic	8 x 12	0 - 1.15	0 - 4	
Supersonic Wind Tunnels				
4-ft	4 x 4	1.2 - 4	6 - 17	2-D Transonic Insert
Calspan				
Transonic Wind Tunnels				
8-ft	8 x 8	0 - 1.35	0 - 12.5	Captive Trajectory, Pressurized
Supersonic Wind Tunnels				
Ludwieg Tube	60-in dia Free Jet	1.2 - 4.5	0.04 - 18	
Hypersonic Wind Tunnels				
96-in Shock Tunnel	Variable 24 to 96-in dia	6.5 - 24	0.001 - 75	High R_e
48-in Shock Tunnel	Variable 24 to 48-in dia	5.5 - 20	0.004 - 50	High R_e
FluiDyne				
Transonic Wind Tunnels				
66-in	66 x 66-in	0 - 1.0	0 - 4.5	
Hypersonic Wind Tunnels				
20-in	20-in dia	11, 14	0.7 - 2.2	Standby

U.S. INDUSTRY

Location and Facility Description	Test Section (ft)	Speed Range (Mach No.)	Reynolds Number (per ft x 10^{-6})	Comments
General Applied Science				
Hypersonic Wind Tunnels				
High Temp Storage Heater	25 x 25-in	0.1 - 12	0 - 15	Propulsion
VAH	15 x 15-in	2.7 - 8.0	0 - 17	Propulsion
HPB	13 x 13-in	0.1 - 7.0	0 - 30	Propulsion
General Dynamics				
Subsonic Wind Tunnels				
8 x 12-ft	8 x 12	0.37	2.5	
w/Tandem V/STOL	16 x 20	0.2 - 0.08	0.1 - 0.6	
Grumman				
Subsonic Wind Tunnels				
7 x 10-ft	7 x 10	0.18	1.73	Propulsion Simulation
Transonic Wind Tunnels				
26-in	26 in Slotted Oct	0.20 - 1.27	2.10 - 27.8	Flutter, Propulsion Simulation
Supersonic Wind Tunnels				
15-in	15 x 15-in	1.75, 2.2, 2.5, 3, 3.5, 4	10 - 60	
Hypersonic Wind Tunnels				
36-in	36-in dia	8, 10, 14	0.2 - 4.5	Standby
Lockheed-CA				
Subsonic Wind Tunnels				
8 x 12-ft	8 x 12	0 - 293 ft/sec	1.7	Ground Effects
Icing Tunnel	4 x 2.5	88 - 308 ft/sec	2	Icing
Transonic Wind Tunnels				
Free Jet	6 x 7	0.2 - 2.65	0 - 12	Propulsion
4-ft Trisonic	4 x 4	0.2 - 5.0	2 - 30	High R_e, Polysonic

U.S. INDUSTRY

Location and Facility Description	Test Section (ft)	Speed Range (Mach No.)	Reynolds Number (per ft x 10^{-6})	Comments
Lockheed-CA				
Hypersonic Wind Tunnels				
30-in	30-in dia Free Jet	8, 10	0.42 - 2.2	Standby
Lockheed-GA				
Subsonic Wind Tunnels				
Low Speed	#1 30 x 26	14 - 146 ft/sec	0 - 1	
	#2 16 x 23	29 - 293 ft/sec	0 - 2	
Transonic Wind Tunnels				
Compressible Flow	20 x 28	0.2 - 1.3	5 - 55	2-D, Pressurized
McDonnell Douglas-El Sequndo				
Transonic Wind Tunnels				
4-ft Trisonic	4 x 4	0.2 - 5.0	0.25 - 30	High R_e, Polysonic
1-ft	1 x 1	0.5 - 1.2	20 - 60	2-D, Cryogenic Mode
Hypersonic Wind Tunnels				
2-ft	24-in dia Free Jet	6, 8, 10	1.2 - 11.2	Standby
McDonnell Douglas-St. Louis				
Subsonic Wind Tunnels				
Low Speed	8.5 x 12	0 - 0.3	0.2 - 2	
Mini Speed or Interim V/STOL	15 x 20	0 - 0.10	0 - 0.75	Propulsion Simulation
Transonic Wind Tunnels				
Polysonic	4 x 4	0.2 - 5.8	0.1 - 50	High R_e, Polysonic
Northrop				
Subsonic Wind Tunnels				
7 x 10-ft	7 x 10	0.37	2.4	Flutter
Transonic Wind Tunnels				
24-in Trisonic	2 x 2	0.4 - 1.35, 1.5, 2, 2.2, 3	0.2 - 30	Polysonic

U.S. INDUSTRY

Location and Facility Description	Test Section (ft)	Speed Range (Mach No.)	Reynolds Number (per ft x 10^{-6})	Comments
Northrop				
Hypersonic Wind Tunnels				
30-in	30-in dia Free Jet	6, 10, 14	0.02 - 3.5	Standby
Rockwell International–Columbus				
Subsonic Wind Tunnels				
7 x 10-ft	7 x 10	370 ft/sec	2.1	Propulsion Simulation
w/Tandem V/STOL	16 x 14	115 ft/sec	0.8	V/STOL
Rockwell International–Los Angeles				
Subsonic Wind Tunnels				
NAAL	8 x 11	0.28	2	Flutter
Transonic Wind Tunnels				
7-ft	7 x 7	0.1 - 3.5	2 - 19	High R_e, Polysonic, Flutter, Acoustics
Sandia Laboratories				
Hypersonic Wind Tunnels				
18-in	18-in dia	5, 8, 14	0.2 - 9.7	
United Technologies				
Subsonic Wind Tunnels				
4 x 6-ft	4 x 6	0.13	0.9	
Large Subsonic	#1 18 Oct, 40 L	0.26	1.6	
	#2 8 Oct, 16 L	0.9	4.5	
Vought Corporation				
Subsonic Wind Tunnels				
7 x 10-ft	7 x 10	44 - 337 ft/sec	2.5	Captive Trajectory,
w/Tandem V/STOL	15 x 20	14 - 76 ft/sec	0.06 - 0.5	Moving Ground, V/STOL
Large Ground Effects Facility	12 x 16	51 ft/sec	0.32	V/STOL, Ground Effects
Transonic Wind Tunnels				
High Speed	4 x 4	0.2 - 5.0	2 - 38	High R_e, Polysonic, Captive Trajectory Flutter

U.S. UNIVERSITIES

Location and Facility Description	Test Section (ft)	Speed Range (Mach No.)	Reynolds Number (per ft x 10^{-6})	Comments
GALICIT				
Subsonic Wind Tunnels				
10-ft	10 dia x 10 L	0.02 -.2 2	0.12 - 1.40	
Georgia Institute of Technology				
Subsonic Wind Tunnels				
7 x 9-ft	7 x 9	0 - 0.22	0 - 1.6	
Low Turbulence	3.5 x 3.5	73 ft/sec	0.5	
Massachusetts Institute of Technology				
Subsonic Wind Tunnels				
Acoustic	7.5 x 5	15 - 88 ft/sec	0.1 - 0.6	Acoustic
Wright Bros.	7.5 x 10 Elliptical	Up to 0.36 @ 0.25 bar	Up to 2.25 @ 1.5 bar	Pressurized
Texas A&M University				
Subsonic Wind Tunnels				
7 x 10-ft	7 x 10	0 -.2 5	0 - 1.9	High Pressure Air for Powered Models
University of Oklahoma				
Subsonic Wind Tunnels				
Subsonic Wind Tunnel	4 x 6	30 - 265 ft/sec	0.2 - 1.6	
University of Washington				
Subsonic Wind Tunnels				
8 x 12-ft	8 x 12	0 - 302 ft/sec	0 - 1.8	
Virginia Polytechnic Institute				
Subsonic Wind Tunnels				
6 x 6-ft	6 x 6	250 ft/sec	1.5	Curved Flow/Stability
Wichita State University				
Subsonic Wind Tunnels				
7 x 10-ft	7 x 10	0 - 264	0 - 1.8	

FOREIGN INSTALLATIONS

Location and Facility Description	Test Section (ft)	Speed Range (Mach No.)	Reynolds Number (per ft x 10^{-6})	Comments
CANADA				
Subsonic Wind Tunnels				
9 x 9-m	30 x 30	180 ft/sec	0.3	
10 x 20-ft	20 x 10	205 ft/sec	0 - 1.3	Propulsion
2 x 3-m	6 x 9	322 ft/sec	0.6	
Transonic Wind Tunnels				
NAE 5 x 5-ft Blowdown				
3-Dimensional	5 x 5	0.1 - 4.25	24 @ M = 2.25	High R_e, Polysonic
2-Dimensional	5 x 1.75	0.1 - 0.95	47 @ M = 0.95	High R_e, 2-D
FRANCE				
Subsonic Wind Tunnels				
CEPRA 19	#1 6 dia, 36 L	327 ft/sec	Up to 6.6	2-D, Anechoic
	#2 9 dia, 36 L	287 ft/sec	Up to 4.1	3-D, Anechoic
F1	11 x 15	409 ft/sec	<5.7	High R_e
F2	4 x 5	327 ft/sec	1.8	
S1-MA	26 dia, 45 L	0 - 1	2.5 @ M = 0.5	Subsonic Test Section
S2-CH	9 dia, 16 L	393 ft/sec	2.5	
SV4	13 dia	130 ft/sec	0.8	Vertical Spin
Transonic Wind Tunnels				
S1-MA	26 dia, 45 L	0 - 1	4.1 @ M = 1	Transonic Test Section
S2-MA	#1 5.8 - 5.7	0.1 - 1.3	1.6 - 8.9	Transonic Test Section
S3-MA	#1 2.6 - 1.8	0.1 - 1.1	19.5	Transonic Test Section, 2-D Insert
S3-CH	2.9 x 2.6	0.3 - 1.10	3.6	
T-2	1.3 x 1.3	Up to 0.9 w/ adaptive walls	51	High R_e, Cryogenic
Sigma 4	2.7 x 2.7	0.3 - 2.8	–	
Supersonic Wind Tunnels				
C-4	1.3 x 1.3	1.35 - 4.3	3.0 - 9.7	
S2-MA	#2 6.2 - 5.7	1.5 - 3.1	1.6 - 8.9	Supersonic Test Section
S3-MA	#2 2.6 - 2.5	1.2, 1.5, 2, 3.4, 4.5	19.5	Supersonic Test Section

FOREIGN INSTALLATIONS

Location and Facility Description	Test Section (ft)	Speed Range (Mach No.)	Reynolds Number (per ft x 10^{-6})	Comments
FRANCE				
Hypersonic Wind Tunnels				
C-2	3.9 dia	8 - 16	0.3	
R2-CH	#1 7.5-in dia	3.0 - 4.0	0.5	
	#2 12-in dia	5.0 - 7.0	0.5	
R3-CH	#1 13-in dia	3.0 - 7.0	0.6	
	#2 13-in dia	10	0.6	
S4-MA	2.2	6	0.9 - 8.2	
GERMANY				
Subsonic Wind Tunnels				
3.25 x 2.8-m (NWB)	10 x 9	Open 246 ft/sec	0.3	
		Closed 295 ft/sec	1.8	
3 x 3-m (NWG)	9 x 9	213 ft/sec	1.3	
High Pressure (HDG)	2 x 2	114 ft/sec	60	High R_e, Pressurized
KKK	7.8 x 7.8	100K : 0.35	10	Cryogenic
Transonic Wind Tunnels				
1-m (TWG)	3 x 3	0.5 - 2.0	54 @ M = 1.0	High R_e
High Speed (HKG)	#1 2 x 2	1.22 - 2.5		
	#2 2 x 2	0.4 - 0.95	4.4 @ M = 0.95	
Transonic Tunnel (TWB)	1 x 2	0.3 - 0.95	3.6 - 25	2-D
Supersonic Wind Tunnels				
High Speed (HMK)	11 x 11-in	0.4 - 0.7	50	High R_e
	Fixed Nozzle	1.57 - 4.15		
Trisonic Tunnel (TMK)	23 x 23-in	0.5 - 4.5	1.8 - 24	Polysonic
Hypersonic Wind Tunnels				
H2K	24-in dia	4.5 - 11.2	9 @ M = 6	Standby
			0.3 @ M = 11.2	
INDIA				
Transonic Wind Tunnels				
1.2-m	4 x 4	0.2 - 4.0	24.4	Captive Trajectory, Polysonic

FOREIGN INSTALLATIONS

Location and Facility Description	Test Section (ft)	Speed Range (Mach No.)	Reynolds Number (per ft x 10^{-6})	Comments
JAPAN				
Subsonic Wind Tunnels				
6-m (NAL)	#1 21 x 18	198 ft/sec	1.2	
	#2 18 x 15	230 ft/sec	1.5	
3.5-m (KHI)	Closed #1 11 x 11	0 - 114 ft/sec	0.74	
	Open #2 8 x 9	0 - 196 ft/sec	1.36	
2-m (Mitsubishi)	6 x 6.5	278 ft/sec	1.8	
Convertible Tunnel (TRDI)	#1 11 x 11	50 - 190 ft/sec	1.4	
	#2 20 x 20	30 - 60 ft/sec	1.4	
	#3 13 Oct	50 - 110 ft/sec	1.4	
Cryogenic (U. of Tsukubu)	1.6 x 1.6	44 - 212 ft/sec	60	High R_e, Cryogenic
Low Speed (TRDI)	8.2 dia x 11.5 L	50 - 190 ft/sec	1.4	Flutter
Low Speed (FHI)	6.56 x 6.56	0 - 197 ft/sec	1.5	Flutter
Transonic Wind Tunnels				
2-m (NAL)	6.5 x 6.5	0.3 - 1.4	1.5 - 6	
2 x 2-ft (FHI)	2 x 2	0.2 - 4.0	3.2 - 3.5	Polysonic
60-cm Trisonic (Mitsubishi)	2 x 2	0.4 - 4.0	4.5 - 19	Polysonic
2-D (KHI)	1.3 x 0.32	0.4 - 1.2	4.6 - 14.4	2-D
RENO (NAL)	11.8 x 39.4-in	0.2 - 1.15	14 @ M = 0.8	2-D
Supersonic Wind Tunnels				
1-m (NAL)	3.28 x 3.28	1.4 - 4.0	9 - 18	
Hypersonic Wind Tunnels				
50-cm	1.6 dia	5, 7, 9, 11		No Data Sheet
NETHERLANDS				
Subsonic Wind Tunnels				
DNW				
9.5 x 9.5-m	31 x 31	203 ft/sec	1.2	Interchangeable Test
8 x 6-m	20 x 26	Closed 0.32	0.22	Sections, Acoustics
		Open 0.24	0.7	
6 x 6-m	20 x 20	475 ft/sec	1.8	
3 x 2.25-m (LST)	9 x 6	278 ft/sec	1.5	

FOREIGN INSTALLATIONS

Location and Facility Description	Test Section (ft)	Speed Range (Mach No.)	Reynolds Number (per ft x 10^{-6})	Comments
NETHERLANDS				
Transonic Wind Tunnels				
HST	5.2 - 6.5	0 - 1.27	12 @ M = 0.5	
Supersonic Wind Tunnels				
SST	4 x 4	1.2 - 4.0	30 @ M = 2.5	
UNITED KINGDOM				
Subsonic Wind Tunnels				
24-ft (Farnborough)	23.7 dia	168 ft/sec	0.7	Anechoic
18-ft (Warton)	18 x 18	38 - 71 ft/sec	0.2 - 0.4	V/STOL
15-ft (Hatfield)	15 x 15	0 - 140 ft/sec	0 - 0.9	
5-m (Farnborough)	13 x 16	0.33	5.4	High R_e, Pressurized
13 x 9-ft (Weybridge)	9 x 13	200 - 300 ft/sec	0 - 2.2	
12 x 10-ft (Filton)	10 x 12	0 - 278 ft/sec	0 - 1.8	
13 x 9-ft (Bedford)	9 x 13	16 - 297 ft/sec	0.9 - 1.9	
11.5 x 8.5-ft (Farnborough)	8.5 x 11.5	16 - 365 ft/sec	2.2	
9 x 7-ft (Woodford)	7 x 9	88 ft/sec	0 - 4.3	
9 x 7-ft (Hatfield)	6.7 x 8.7	0 - 250 ft/sec	0 - 1.6	
2.7 x 2.1 (Warton)	6 x 8	0 - 218 ft/sec	0.03 - 1.5	
7 x 5-ft (Brough)	5 x 7	278 ft/sec	1.6 - 3	
3 x 2-ft (Weybridge)	2 x 3	0.40 - 0.92	2.6 - 4.5	
Transonic Wind Tunnels				
8-ft (Bedford)	8 x 8	0.1 - 0.9	11 @ M = 0.9	Transonic Mode
		1.35 - 2.5	3.4 @ M = 2.5	Supersonic Mode
8 x 6-ft (Farnborough)	6 x 8	0 - 1.25	7.3 @ M = 0.3	
			2.7 @ M = 1.25	
4-ft (Warton)	4 x 4	0.4 - 4.0	24	High R_e, Polysonic, Flutter
27 x 27-in (Brough)	27 x 27-in	0.1 - 2.5	0.8 - 20	
TWT (Bedford)	8 x 9	0 - 1.4	1.5 - 5.5	

FOREIGN INSTALLATIONS

Location and Facility Description	Test Section (ft)	Speed Range (Mach No.)	Reynolds Number (per ft x 10^{-6})	Comments
UNITED KINGDOM				
Supersonic Wind Tunnels				
3 x 4-ft (Bedford)	3 x 4	2.5 - 5.0	12 @ M = 4.5	
30 x 27-in (Woodford)	30 x 27-in	1.6 - 3.5	17 @ M = 1.6 9 @ M = 3.5	
SWT (Bedford)	2.5 x 2.25 m	1.4 - 3.0	1.0 - 4.3	
Hypersonic Wind Tunnels				
Guided Weapons	1.4 x 1.4	1.7 - 6.0	-	
M4T (Bedford)	1.0 x 1.33	4.0 - 5.0	23 - 14	
M7T (Bedford)	1.0 dia	7.0	10 - 15	

A P P E N D I X

B

APPENDIX B

SUBSONIC WIND TUNNELS

Location and Facility Description	Test Section (ft)	Speed Range (ft/sec)	Reynolds Number (per ft x 10^{-6})	Comments
U.S. NASA				
Ames Research Center				
80 x 120-ft	80 x 120	M = 0.15	0 - 1	High R_e, Propulsion
40 x 80-ft	40 x 80	M = 0.45	0 - 3	High R_e
12-ft Pressure	11.3 dia	M = 0.6	0 - 9	High R_e, Pressurized
7 x 10-ft (1)	7 x 10	M = 0 - 0.33	0 - 2.6	V/STOL
7 x 10-ft (2)	7 x 10	M = 0.33	0 - 2.6	Rotorcraft, Army Facility
Langley Research Center				
30 x 60-ft	30 x 60	38 - 132	1	Open Throat
4 x 7-m	14.5 x 21.8	318	2.1	Moving Ground, V/STOL
7 x 10-ft	6.6 x 9.6	M = 0.2 - 0.9	0.1 - 3.2	
Low-Turbulence Pressure (LTPT)	7.5 x 3	M = 0.05 - 0.5	0.1 - 15	2-D, Pressurized
Vertical Spin Tunnel	20 dia, 25 height	90 ft/sec	0.6	Vertical Spin
Lewis Research Center				
9 x 15-ft	9 x 15	M = 0 - 0.2	0 - 1.4	Propulsion
AWT (Proposed)	20 dia	M = 0.9	3.5	Icing, Propulsion, No Data Sheet
IRT	6 x 9	M = 0 - 0.5	3.3	Icing
U.S. DOD				
David Taylor Naval Ship R&D Center				
8 x 10-ft	8 x 10	30 - 275	0 - 1.77	Flutter
Wright Aeronautical Laboratories				
Vertical Tunnel	12 x 15	0 - 150	0 - 0.91	
U.S. INDUSTRY				
Boeing Vertol				
20 x 20-ft V/STOL	20 x 20	M = 0.325	0 - 2.3	
Boeing-Seattle				
9 x 9-ft	9 x 9	M = 0.36	2	Propulsion
Low Speed Research	8 x 5	M = 0.18	1.2	

SUBSONIC WIND TUNNELS

Location and Facility Description	Test Section (ft)	Speed Range (ft/sec)	Reynolds Number (per ft x 10^{-6})	Comments
U.S. INDUSTRY				
General Dynamics				
8 x 12-ft	8 x 12	M = 0.37	2.5	
w/Tandem V/STOL	16 x 20	M = 0.2 - 0.08	0.1 - 0.6	
Grumman				
7 x 10-ft	7 x 10	M = 0.18	1.73	Propulsion Simulation
Lockheed-CA				
8 x 12-ft	8 x 12	0 - 293	1.7	Ground Effects
Icing Tunnel	4 x 2.5	88 - 308	2	Icing
Lockheed-GA				
Low Speed	#1 30 x 26	146	0 - 1	
	#2 16 x 23	293	0 - 2	
McDonnell Douglas-St. Louis				
Low Speed	8.5 x 12	M = 0 - 0.3	0.2 - 2	
Mini Speed or Interim V/STOL	15 x 20	M = 0 - 0.10	0 - 0.75	Propulsion Simulation
Northrop				
7 x 10-ft	7 x 10	M = 0.37	2.4	Flutter
Rockwell-Columbus				
7 x 10-ft	7 x 10	370	2.1	Propulsion Simulation
w/Tandem V/STOL	16 x 14	115	0.8	V/STOL
Rockwell-Los Angeles				
NAAL	8 x 11	M = 0.28	2	Flutter
United Technologies				
4 x 6-ft	4 x 6	M = 0.13	0.9	
Large Subsonic	#1 18 Oct, 40 L	M = 0.26	1.6	
	#2 8 Oct, 16 L	M = 0.9	4.5	
Vought				
7 x 10-ft	7 x 10	44 - 337	2.5	Captive Trajectory,
w/Tandem V/STOL	15 x 20	14 - 76	0.06 - 0.5	Moving Ground, V/STOL
Large Ground Effects Facility	12 x 16	51	0.32	V/STOL, Ground Effects

SUBSONIC WIND TUNNELS

Location and Facility Description	Test Section (ft)	Speed Range (ft/sec)	Reynolds Number (per ft x 10^{-6})	Comments
U.S. UNIVERSITIES				
GALCIT				
10-ft	10 dia, 10 L	M = 0.02 - 0.22	0.12 - 1.40	
Georgia Institute of Technology				
7 x 9-ft	7 x 9	M = 0 - 0.22	0 - 1.6	
Low Turbulence	3.5 x 3.5	73	0.5	
Massachusetts Institute of Technology				
Acoustic	7.5 x 5	15 - 88	0.1 - 0.6	Acoustic
Wright Brothers	7.5 x 10 Elliptical Test Section	Up to 0.36 @ 0.25 bar	Up to 2.25 @ 1.5 bar	Pressurized
Texas A&M University				
7 x 10-ft	7 x 10	M = 0 - 2.5	0 - 1.9	High Pressure Air for Powered Models
University of Oklahoma				
Subsonic Tunnel	4 x 6	30 - 265	0.2 - 1.6	
University of Washington				
8 x 12-ft	8 x 12	0 - 302	0 - 1.8	
Virginia Polytechnic Institute				
6 x 6-ft	6 x 6	250	1.5	Curved Flow/Stability
Wichita State				
7 x 10-ft	7 x 10	0 - 264	0 - 1.8	
CANADA				
9 x 9-m	30 x 30	180	0.3	
10 x 20-ft	20 x 10	205	0 - 1.3	Propulsion
2 x 3-m	6 x 9	322	0.6	
FRANCE				
CEPRA 19	#1 6 dia, 36 L	327	Up to 6.6	2-D, Anechoic Tunnel
	#2 9 dia, 36 L	287	Up to 4.1	3-D, Anechoic Tunnel

SUBSONIC WIND TUNNELS

Location and Facility Description	Test Section (ft)	Speed Range (ft/sec)	Reynolds Number (per ft x 10^{-6})	Comments
FRANCE				
F1	11 x 15	409	5.7	High R_e
F2	4 x 5	327	1.8	
S-1 MA	26 dia	M = 0 - 1	2.5 @ M = 0.5	Also Transonic
S2-CH	9 dia, 16 L	393	2.5	
SV4	13 dia	130 (max)	0.8	Vertical Spin
GERMANY				
3.25 x 2.8-m (NWB)	10 x 9	Open 246	0.3	
		Closed 295	1.8	
3 x 3-m (NWG)	9 x 9	213	1.3	
High Pressure (HDG)	2 x 2	114	60	High R_e, Pressurized
KKK	7.8 x 7.8	100K : M = 0.35	10	Cryogenic
JAPAN				
6-m (NAL)	#1 21 x 18	198	1.2	
	#2 18 x 15	230	1.5	
3.5-m (KHI)	Closed 11 x 11	0 - 114	0.74	
	Open 8 x 9	0 - 196	1.36	
2-m (Mitsubishi)	6 x 6.5	278	1.8	
Convertible Tunnel (TRDI)	#1 11 x 11	50 - 190	1.4	
	#2 20 x 20	30 - 60	1.4	
	#3 13 Oct	50 - 110	1.4	Vertical Spin
Cryogenic (U. of Tsukubu)	1.6 x 1.6	44 - 212	60	High R_e, Cryogenic
Low Speed (TRDI)	8.2 dia x 11.5 L	50 - 190	1.4	Flutter
Low Speed (KHI)	6.56 x 6.56	0 - 197	1.5	Flutter
NETHERLANDS				
DNW				
9.5 x 9.5-m	31 x 31	203	1.2	
8 x 6-m	20 x 26	Closed M = 0.32	2.2	Interchangeable Test Sections, Acoustics
		Open M = 0.24	1.7	
6 x 6-m	20 x 20	475	1.8	
3 x 2.25-m (LST)	9 x 6	278	1.5	

SUBSONIC WIND TUNNELS

Location and Description Facility	Test Section (ft)	Speed Range (ft/sec)	Reynolds Number (per ft x 10^{-6})	Comments
UNITED KINGDOM				
24-ft (Farnborough)	23.7 dia	168	0.7	Anechoic
18-ft (Warton)	18 x 18	38 - 71	0.2 - 0.4	V/STOL
15-ft (Hatfield)	15 x 15	0 - 140	0 - 0.9	
5-m (Farnborough)	13 x 16	M = 0.33	5.4	High R_e, Pressurized
13 x 9-ft (Weybridge)	9 x 13	200 - 300	0 - 2.2	
12 x 10-ft (Filton)	10 x 12	0 - 278	0 - 1.8	
13 x 9-ft (Bedford)	9 x 13	16 - 297	0.09 - 1.9	
11.5 x 8.5-ft (Farnborough)	8.5 x 11.5	16 - 365	2.2	
9 x 7-ft (Woodford)	7 x 9	88	0 - 4.3	
9 x 7-m (Hatfield)	8.7 x 6.7	0 - 250	0 - 1.6	
2.7 x 2.1 (Warton)	6 x 8	0 - 218	0.03 - 1.5	
7 x 5-ft (Brough)	5 x 7	278	1.6 - 3	
3 x 2-ft (Weybridge)	2 x 3	M = 0.40 - 0.92	2.6 - 4.5	

A P P E N D I X

C

APPENDIX C

TRANSONIC WIND TUNNELS

Location and Facility Description	Test Section (ft)	Speed Range (Mach No.)	Reynolds Number (per ft x 10^{-6})	Comments
U.S. NASA				
Ames Research Center				
14-ft	13.5 x 13.7	0.5 - 1.2	2.6 - 4.2	Standby
11-ft (Unitary)	11 x 11	0.4 - 1.4	1.26 - 9.4	
2 x 2-ft	2 x 2	0.2 - 1.4	0.5 - 8.7	
Langley Research Center				
16-ft	15.5 x 15.5	0.2 - 1.3	1.2 - 4.2	Propulsion Integration
8-ft TPT	7.1 x 7.1	0.2 - 1.3	0.6 - 6	Pressurized
0.3-m 2-D Test Section	8 x 24-in	0.2 - 0.9	120	Cryogenic
0.3-m Flex Wall Test Section	13 x 13-in	0.2 - 1.1	120	Cryogenic
6 x 28-in	6 x 28-in	0.2 - 1.2	4.0 - 25	2-D
NTF	8.2 x 8.2	0.2 - 1.2	145	Cryogenic, Pressurized
Transonic Dynamics Tunnel (TDT)	16 x 16	0 - 1.2	2.8 Air 8.5 Freon	Flutter
Marshall Space Flight Center				
High R_e	32-in dia	0.3 - 3.50	7 - 200	2-D, High R_e, Pressurized
U.S. DOD				
Arnold Engineering Development Center				
16T	16 x 16	0 - 1.6	0.1 - 6.0	Propulsion, Captive Trajectory
4T	4 x 4	0.1 - 1.3, 1.6, 2.0	2.0 - 6.5 @ M = 1.6 1.3 - 6.1 @ M = 2	Captive Trajectory
David Taylor Naval Ship R&D Center				
7 x 10-ft	7 x 10	0.25 - 1.17	1 - 5	Captive Trajectory
U.S. INDUSTRY				
Boeing, Seattle				
Transonic	8 x 12	0 - 1.15	0 - 4	
Calspan				
8-ft	8 x 8	0 - 1.35	0 - 12.5	Captive Trajectory, Pressurized

TRANSONIC WIND TUNNELS

Location and Facility Description	Test Section (ft)	Speed Range (Mach No.)	Reynolds Number (per ft x 10^{-6})	Comments
U.S. INDUSTRY				
FluiDyne				
66-in	66 x 66-in	0 - 1.0	0 - 4.5	
Grumman				
26-in	26 in Slotted Oct	0.20 - 1.27	2.10 - 27.8	Flutter, Propulsion Simulation
Lockheed-CA				
Free Jet	6 x 7	0.2 - 2.65	0 - 12.0	Propulsion
4-ft Trisonic	4 x 4	0.2 - 5.0	2 - 30	High R_e, Polysonic
Lockheed-GA				
Compressible Flow	20 x 28-in	0.2 - 1.3	5 - 55	2-D, Pressurized
McDonnell Douglas-El Segundo				
4-ft Trisonic	4 x 4	0.2 - 5.0	0.25 - 30	Polysonic
1-ft	1 x 1	0.5 - 1.2	20 - 60	2-D, Cryogenic Mode
McDonnell Douglas-St. Louis				
Polysonic	4 x 4	0.2 - 5.8	4 - 50	Polysonic
Northrop				
24-in Trisonic	2 x 2	0.4 - 1.35 1.5, 2, 2.2, 3	0.2 - 30	Polysonic
Rockwell-Los Angeles				
7-ft	7 x 7	0.1 - 3.5	2 - 19	Flutter, Acoustic, Polysonic
Vought				
High Speed	4 x 4	0.2 - 5.0	2 - 38	Captive Trajectory, Flutter, Polysonic
CANADA				
NAE 5 x 5-ft Blowdown				
3-Dimensional	5 x 5	0.1 - 4.25	24 @ M = 2.25	High R_e, Polysonic
2-Dimensional	5 x 1.75	0.1 - 0.95	47 @ M = 0.95	2-D, High R_e

TRANSONIC WIND TUNNELS

Location and Facility Description	Test Section (ft)	Speed Range (Mach No.)	Reynolds Number (per ft x 10^{-6})	Comments
FRANCE				
S-1 MA	26 dia x 45 L	0 - 1	4.1 @ M = 1	Also listed as Subsonic
S-2 MA	#1 5.8 x 5.7	0.1 - 1.3	1.6 - 8.9	Transonic Test Section
S-3 MA	#1 2.6 x 1.8	0.1 - 1.1	19.5	Transonic Test Section, 2-D Insert
S3-CH	2.9 x 2.6	0.3 - 1.10	3.6	
T-2	1.3 x 1.3	Up to 0.9 w/ adaptive walls	51	High R_e, Cryogenic
SIGMA 4	3 x 3	0.3 - 2.8	–	
GERMANY				
1-m (TWG)	3 x 3	0.5 - 2.0	54 @ M = 1.0	High R_e
High Speed (HKG)	#1 2 x 2	1.22 - 2.5		
	#2 2 x 2	0.4 - 0.95	4.4 @ M = 0.95	
Transonic Tunnel (TWB)	1 x 2	0.3 - 0.95	3.6 - 25	2-D Test Section
Trisonic Tunnel (TMK)	23 x 23 in	0.5 - 4.5	1.8 - 24	Polysonic
INDIA				
1.2-m	4 x 4	0.2 - 4.0	24.4	Captive Trajectory, Polysonic
JAPAN				
2-m (NAL)	6.5 x 6.5	0.3 - 1.4	1.5 - 6	
2 x 2-ft (KHI)	2 x 2	0.2 - 4.0	3.2 - 3.5	Polysonic
60-cm Trisonic (Mitsubishi)	2 x 2	0.4 - 4.0	4.5 - 19	Polysonic
2-D (KHI)	1.3 x 0.32	0.4 - 1.2	4.6 - 14.4	2-D
RENO (NAL)	11.8 x 39.4 in	0.2 - 1.15	14 @ M = 0.8	2-D
NETHERLANDS				
HST	5.2 x 6.5	0 - 1.27	12 @ M = 0.5	

TRANSONIC WIND TUNNELS

Location and Facility Description	Test Section (ft)	Speed Range (Mach No.)	Reynolds Number (per ft x 10^{-6})	Comments
UNITED KINGDOM				
8-ft (Bedford)	8 x 8	0.1 - 0.9	11.6 @ M = 0.9	Transonic Mode
8 x 6-ft (Farnborough)	6 x 8	0 - 1.25	7.3 @ M = 0.3 2.7 @ M = 1.25	
4-ft (Warton)	4 x 4	0.4 - 4.0	24	High R_e, Polysonic, Flutter
27 x 27-in (Brough)	27 x 27-in	0.1 - 2.5	0.8 - 20	Polysonic
TWT (Bedford)	8 x 9	0 - 1.4	1.5 - 5.5	

APPENDIX

D

SUPERSONIC WIND TUNNELS

Location and Facility Description	Test Section (ft)	Speed Range (Mach No.)	Reynolds Number (per ft x 10^{-6})	Comments
U.S. NASA				
Ames Research Center				
9 x 7-ft (Unitary)	9 x 7	1.55 - 2.5	0.8 - 6.5	Captive Trajectory
8 x 7-ft (Unitary)	8 x 7	2.4 - 3.5	0.6 - 5.0	Captive Trajectory
6 x 6-ft	6 x 6	0.25 - 2.2	0.5 - 5.0	
Langley Research Center				
Unitary Tunnel	#1 4 x 4	1.47 - 2.86	0.5 - 12.2	
	#2 4 x 4	2.29 - 4.63	0.5 - 9.5	
Lewis Research Center				
10 x 10-ft	Closed 10 x 10	2 - 3.5	0.12 - 3.4	Propulsion
	Open 10 x 10	2 - 3.5	2.1 - 2.7	
8 x 6-ft	8 x 6	0.4 - 2.0	3.6 - 4.8	Propulsion
1 x 1-ft	1 x 1	1.6 - 5.0	1.5 - 36	Internal Fluid Dynamics
U.S. DOD				
Arnold Engineering Development Center				
16S	16 x 16	1.5 - 4.75	0.1 - 2.6	Propulsion
APTU	16 dia	0 - 4.5	-	Propulsion, Ramjet
von Karman A	3.3 x 3.3	1.5 - 6	0.3 - 9.2	Captive Trajectory
Naval Surface Weapons Center				
Boundary Layer	12 x 12-in	3 - 5	0.2 - 24	Vertical Test Section
Supersonic #2	16 x 16-in	0.3 - 5	0.5 - 21	Open Jet
Wright Aeronautical Laboratories				
Mach 3 High R_e	8.2 x 8-in	3	10 - 100	High R_e
U.S. INDUSTRY				
Boeing-Seattle				
4-ft	4 x 4	1.2 - 4	6 - 17	2-D Transonic Insert
Calspan				
Ludwieg Tube	60-in dia Free Jet	1.2 - 4.5	0.04 - 18	

SUPERSONIC WIND TUNNELS

Location and Facility Description	Test Section (ft)	Speed Range (Mach No.)	Reynolds Number (per ft x 10^{-6})	Comments
U.S. INDUSTRY				
Grumman 15-in	15 x 15-in	1.75, 2.2, 2.5, 3, 3.5, 4	10 - 60	
Lockheed-CA 4-ft Trisonic	4 x 4	0.2 - 5.0	2 - 30	High R_e, Polysonic
McDonnell Douglas-El Segundo 4-ft Trisonic	4 x 4	0.2 - 5.0	0.25 - 30	High R_e, Polysonic
McDonnell Douglas-St. Louis Polysonic	4 x 4	0.5 - 5.8	2 - 50	High R_e, Polysonic
Northrop 24-in Trisonic	2 x 2	0.4 - 1.35 1.5, 2, 2.2, 3	0.2 - 30	Polysonic
Rockwell-Los Angeles 7-ft	7 x 7	0.1 - 3.5	2 - 19	High R_e, Polysonic, Flutter, Acoustic
Vought High Speed	4 x 4	0.2 - 5.0	2 - 38	High R_e, Polysonic, Captive Trajectory, Flutter
CANADA				
NAE 5 x 5-ft Blowdown 3-D	5 x 5	0.1 - 4.25	24 @ M = 2.25	High R_e, Polysonic
FRANCE				
C-4	1.3 x 1.3	1.35 - 4.3	3.0 - 9.7	
S2-MA	#2 6.2 x 5.7	1.5 - 3.1	1.6 - 8.9	Supersonic Test Section
S3-MA	#2 2.6 x 2.5	1.2, 1.5, 2, 3.4, 4.5	19.5	Supersonic Test Section
GERMANY				
High Speed (HMK)	11 x 11-in Fixed Nozzle	0.4 - 0.7 1.57 - 4.15	50	High R_e
Trisonic Tunnel (TMK)	23 x 23-in	0.5 - 4.5	1.8 - 24	Polysonic

SUPERSONIC WIND TUNNELS

Location and Facility Description	Test Section (ft)	Speed Range (Mach No.)	Reynolds Number (per ft x 10^{-6})	Comments
INDIA				
1.2-m	4 x 4	0.4 - 4.0	24.4	Captive Trajectory, Polysonic
JAPAN				
1-m (NAL)	3.28 x 3.28	1.4 - 4.0	9 - 18	
2 x 2-ft (FHI)	2 x 2	0.2 - 4.0	3.2 - 3.5	Polysonic
60-cm Trisonic (Mitsubishi)	2 x 2	0.4 - 4.0	4.5 - 19	Polysonic
NETHERLANDS				
SST	4 x 4	1.2 - 4.0	30 @ M = 2.5	High R_e, Pressurized
UNITED KINGDOM				
8-ft (Bedford)	8 x 8	0.1 - 0.9 1.35 - 2.5	6 @ M = 1.4	Supersonic Mode
4-ft (Warton)	4 x 4	0.4 - 4.0	24	High R_e, Polysonic, Flutter
3 x 4-ft (Bedford)	3 x 4	2.5 - 5.0	12 @ M = 4.5	
30 x 27-in (Woodford)	27 x 30-in	1.6 - 3.5	17 @ M = 1.6 9 @ M = 3.5	
27 x 27-in (Brough)	27 x 27-in	0.1 - 2.5	0.8 - 20	Polysonic
SWT (Bedford)	2.5 x 2.25 m	1.4 - 3.0	1.0 - 4.3	

A P P E N D I X

E

APPENDIX E

HYPERSONIC WIND TUNNELS

Location and Facility Description	Test Section (ft)	Speed Range (Mach No.)	Reynolds Number (per ft x 10^{-6})	Comments
U.S. NASA				
Ames Research Center				
3.5 Hypersonic	3.5 dia	5, 7, 10	0.3 - 7.4	Standby
Langley Research Center				
8-ft HTT	8 dia	5.8 - 7.3	0.3 - 2.2	Thermal Structures
20-in Mach 6	20 x 20.5-in	6	0.5 - 10.5	
CF_4	20-in dia	6	0.3 - 0.5	
Continuous Flow	31 x 31-in	10	0.4 - 2.4	
Hypersonic Helium Tunnel	22-in dia	17.6 - 22.2	1.1 - 11.3	Aerodynamic Leg
	22 or 36-in	20 or 40	1.3 - 6.0	Fluid Mech. Leg
Hypersonic Nitrogen	16-in dia	18	0.17 - 0.40	
Mach 20 High R_e Helium	5 dia	16.5 - 18	1.9 - 15	
Mach 8 Variable Density Tunnel	18-in dia	8	0.1 - 12.0	
Mach 6 High R_e Tunnel	12-in dia	6	1.8 - 50	High R_e Blowdown
Scramjet	4 dia	4.7 - 6.0	0.13 - 5.2	Propulsion
U.S. DOD				
Arnold Engineering Development Center				
von Karman B	50-in dia	6 or 8	0.3 - 4.7	Captive Trajectory
von Karman C	25 & 50-in dia	4, 10	0.4 - 1.3 @ M = 4 0.3 - 4.7 @ M = 10	Captive Trajectory, Aerothermal
Naval Surface Weapons Center				
Hypersonic #8	17 - 22-in dia	5 - 8	0.6 - 50	High R_e
Hypersonic #8A	24-in dia	18	0.2 - 0.6	
Hypervelocity #9	5 dia	10 - 14.5	0.06 - 20	
Wright Aeronautical Laboratories				
20-in	20-in dia	12, 14	0.4 - 1.0	
Mach 6 High R_e	12-in dia	6	10 - 30	High R_e

HYPERSONIC WIND TUNNELS

Location and Facility Description	Test Section (ft)	Speed Range (Mach No.)	Reynolds Number (per ft x 10^{-6})	Comments
U.S. INDUSTRY				
Calspan				
Ludwieg Tube	60-in dia Free Jet	1.2 - 4.5	0.04 - 18	
96-in Shock Tunnel	Variable 24 to 96-in dia	6.5 - 24	0.001 - 75	High R_e
48-in Shock Tunnel	Variable 24 to 48-in dia	5.5 - 20	0.004 - 50	High R_e
FluiDyne				
20-in	20-in dia	11 - 14	0.7 - 2.2	Standby
General Applied Science				
High Temp Storage Heater	25 x 25-in	0.1 - 12	0 - 15	Propulsion
VAH	15 x 15-in	2.7 - 8.0	0 - 17	Propulsion
HPB	13 x 13-in	0.1 - 7.0	0 - 30	Propulsion
Grumman				
36-in	36-in dia	8, 10, 14	0.2 - 4.5	Standby
Lockheed-CA				
30-in	30-in dia Free Jet	8, 10	0.42 - 2.2	Standby
McDonnell Douglas-CA				
2-ft	2 dia Free Jet	6, 8, 10	1.2 - 11.2	Standby
Northrop				
30-in	30-in dia Free Jet	6, 10, 14	0.02 - 3.5	Standby
Sandia Laboratories				
18-in	18-in dia	5, 8, 14	0.2 - 9.7	
FRANCE				
C-2	3.9 dia	8 - 16	0.3	
R2-CH	#1 7.5-in dia	3.0 - 4.0	0.5	
	#2 13-in dia	5.0 - 7.0	0.5	

HYPERSONIC WIND TUNNELS

Location and Facility Description	Test Section (ft)	Speed Range (Mach No.)	Reynolds Number (per ft x 10^{-6})	Comments
FRANCE				
R3-CH	#1 13-in dia	3.0 - 7.0	0.6	
	#2 13-in dia	10	0.6	
S4-MA	2.2	6	0.9 - 8.2	
GERMANY				
H2K	24-in dia	4.5 - 11.2	9 @ M = 6 0.3 @ M = 11.2	Standby
JAPAN				
50-cm	1.6 dia	5, 7, 9, 11	–	No Data Sheet
UNITED KINGDOM				
Guided Weapons	1.4 x 1.4	1.7 - 6.0	–	
M4T (Bedford)	1.0 - 1.33	4.0 - 5.0	23 - 14	
M7T (Bedford)	1.0 dia	7.0	10 - 15	

APPENDIX

F

APPENDIX F

ENGINE TEST FACILITIES

LOCATION AND FACILITY DESCRIPTION	MASS FLOW (lb/sec)	PRESSURE (psia)	TEMPERATURE (^{o}F)	ALT. RANGE (ft)	COMMENTS AND GROUPINGS
<u>U. S.-- NASA</u>					
<u>Lewis Research Center</u>					
PSL-3	480	60	-50 to +600	5 000 - 80 000	Group 2
PSL-4	480	60; 165	-50; 600; +1200	5 000 - 80 000	Group 2
<u>U.S.--DOD</u>					
<u>Arnold Engineering Development Center</u>					
T-1	450; 800	70; 35	-120 to +650	SL - 80 000	Group 2,4
T-2	450; 800	70; 35	-120 to +650	SL - 80 000	Group 2,4
T-4	450; 800	70; 35	-120 to +650	SL - 80 000	Group 2,4
T-5	50	40	-50 to +650	SL - 80 000	Group 3
T-6	375	70	-30 to +300	SL - 90 000	Group 3 Plume Studies
J-1	500; 700; 1400	120; 40; 13	-65 to +750	SL - 80 000	Group 1,2
J-2	500; 700; 1400	120; 85; 35	-10 to +750	SL - 80 000	Group 1,2
ASTF C-1	1100; 1460	130; 40	-100 to +1020	100 000	Group 1,2 Full Transient Cap.
ASTF C-2	1460; 2760	50; atm inbleed	-100 to +650	100 000	Group 1,2,4 Full Transient Cap.
<u>Naval Air Propulsion Center</u>					
2E	430	41	-65 to +390	SL - 80 000	Group 3 Icing
1E	430	41	-65 to +390	SL - 80 000	Group 3 Icing
3W	100	41	-65 to +220	80 000	Group 1 Icing
3E	700	30	-65 to +650	100 000	Group 2

ENGINE TEST FACILITY

LOCATION AND FACILITY DESCRIPTION	MASS FLOW (lb/sec)	PRESSURE (psia)	TEMPERATURE (^{o}F)	ALT. RANGE (ft)	COMMENTS AND GROUPINGS
4W	100	41	-65 to +220	80 000	Group 3
5W	100	41	-65 to +220	80 000	Group 3
6W	100	41	-65 to +220	80 000	Group 3
U.S.--INDUSTRY					
Allison Gas Turbine Operations					
871	120	2.2 - 30	-75 to +160	SL - 50 000	Group 3 Turboshaft 15 000 HA
872	120	2.2 - 30	-75 to +160	SL - 50 000	Group 3 Turboshaft 8 000 HA
873	120	2.2 - 80	-75 to +160	SL - 45 000	Group 3 Turboshaft 10 000 HA
881	420	1.7 - 26.5	-40 to +210	SL - 50 000	Group 3
885	10	5.5 - 30	-75 to +160	SL - 25 000	Groupp 3 Turboshaft 800 HP
General Electric					
TC-43 and TC-44	450 - 1 000	60 - 43	+100 to +650	60 000	Group 2
TC Al	175	100	-70 to +400	85 000	Group 3
TC-40	450 @ 60 psia 1200 @ SLS	60	-100 to +400	600 (only)	Group 3
Marquardt Company					
TC-2	400	to 1 500	to +5 000	to 110 000	Group 4 Blowdown
TC-8	1200	to 300	to +5 000	to 100 000	Group 4 Blowdown

ENGINE TEST FACILITY

LOCATION AND FACILITY DESCRIPTION	MASS FLOW (lb/sec)	PRESSURE (psia)	TEMPERATURE (^{o}F)	ALT. RANGE (ft)	COMMENTS AND GROUPINGS
Pratt and Whitney					
X-217	750; 1200	12.5; 12.5	-10 to +90	SL - 40 000	Group 1
X-218	750; 1200	12.5; 12.5	-10 to +90	SL - 40 000	Group 1 Transient Testing
X-207	200; 325; 580	45; 35; 12.5	-20; +625; +280	SL - 80 000	Group 2
X-208	200; 325; 580	45; 35; 12.5	-20; +625; +280	SL - 80 000	Group 2
X-209	200; 325; 125	125; 35; 12.5	-20; +725; +650	SL - 80 000	Group 3
CANADA					
National Research Council					
Alt. Test Chamber	0 - 12	1 - 160	-70 to +212	SL - 45 000	Group 3
FRANCE					
CEPr					
R-3	441	30	-85 to +390	65 600	Group 3,4
R-4	441	30	-85 to +370	65 600	Group 3,4
R-5	825	100	+1200	65 600	Group 2,4
S1	221	29	+661	62 000	Group 3,4
C-1	121	17	-86 to +175	36 000	Group 3,4
GERMANY					
University of Stuttgart					
HPT	154	28	-100 to +350	65 600	Group 3,4
JAPAN					
Mitsubishi Heavy Industries					
1007	12	33	-50 to +180	SL - 20 000	Group 3

LOCATION AND FACILITY DESCRIPTION	MASS FLOW (lb/sec)	PRESSURE (psia)	TEMPERATURE (^{o}F)	ALT. RANGE (ft)	COMMENTS
UNITED KINGDOM					
Royal Aircraft Establishment					
ATF C-2	450	2 to 100	Ambinet to +450	50 000	Group 3 Direct Connect
ATF C-3	600	2 to 39	-100 to +880	65 000	Group 2,4 Direct Connect
ATF C-4	500	3 to 40	Ambient to +880	100 000	Group 4 No Direct Connect
ATF C-3W	1400	2 to Atmos	-50 to Ambient	50 000	Group 4 Icing
ATF C-1	450	2 - 100	Ambinet to +450	50 000	Group 4
Rolls Royce					
ATF C-1	400	73	-113 to +355	70 000	Group 3,4
TP 131A	400	165	+841	90 000	Group 4 Blowdown
ATF C-2	400	73	-113 to +355	70 000	Group 3,4

A P P E N D I X

G

APPENDIX G

PROPULSION COMPONENTS FACILITIES

FACILITY NAME/ LOCATION	MAX. FLOW RATE (lb/sec)	MAX. POWER (hp)	TEMPERATURE (^{o}F)	PRESSURE (atm. max)	SPEED (rpm)
NASA Lewis Research Center					
Turbine Component Research Facilities					
Turbine Heat Transfer Fundamentals Facilities	7	N/A	Atmospheric	Atmospheric	N/A
Turbomachinery Aerodynamic Laser Anemometer Facility	10	N/A	Ambient	Atmospheric	N/A
Hot Cascade 2D Cascade Facility	15	N/A	2500	8	N/A
Small Uncooled Turbine Facilities	2 1/2	45	150	3 1/2	45 000
Small Warm Turbine Facility	8	1250	800	8	60 000
High Pressure Turbine Hot Section Facility	200	35 000	2 500	20	23 000
Large Warm Turbine Facilities	25	5 000	950	3	25 000
Compressor Component Research Facilities					
Large Low Speed Centrifugal Compressor Facility	66	1 500	Ambient	Atmospheric Inlet up to 1.18 press. ratio	up to 2050
Transonic Oscillating Cascade Facility	950 ft/sec air velocity	100	Ambinet	Atmoshperic Inlet and Exhaust	--

PROPULSION COMPONENTS FACILITIES

FACILITY NAME/ LOCATION	MAX. FLOW RATE (lb/sec)	MAX. POWER (hp)	TEMPERATURE (°F)	PRESSURE (atm. max)	SPEED (rpm)
Multi-stage Axial Flow Compressor Facility	100 Ambient 200 Super-charging	1 500	-70 to +150	0.3 - 5.3 inlet	up to 18 700
Small Multistage Compressor Facility	13	6 000	Ambient 12000 outlet temp	1.1 - 1.7 inlet plenum press up to 30:1 press ratio	up to 60 000
Small Centrifugal Compressor Facility	13	3 000	Ambient	0.1 - 1.0 inlet	up to 60 000
Small Single Stage Centrifugal Compressor Facility	2	Turbine Drive	+40 to Ambient	0.1 - 1.3 inlet	up to 100 000
Single Stage Axial Flow Compressor	100	3 000	Ambient	0.3 - 1.0 inlet plenum press	up to 19 600
Coaxial Jet Facility	core: 30 fan: 30	--	core: 1 500 fan: 1 500	3:1 press. ratio	--
Fan Acoustic Facility	80	7 000	Ambient	Atmospheric Inlet/Exhaust up to 2.5 press. ratio	up to 20 000
<u>Combustor Component Research Facility</u>					
Low Pressure Combustor	A. 10 B. 3	N/A N/A	1 100 1 800	10 10	N/A N/A
Facilities					
Medium Pressure Combustor Facilities	20	N/A	Ambient - 1 100	30	N/A
High Pressure Combustor Facility (HPC)	200	N/A	Ambient - 850	20 operational 40 standby	N/A

PROPULSION COMPONENTS FACILITIES

FACILITY NAME/ LOCATION	MAX. FLOW RATE (lb/sec)	MAX. POWER (hp)	TEMPERATURE (^{o}F)	PRESSURE (atm. max)	SPEED (rpm)
DOD					
Wright Aeronautical Labs					
Compressor Component Research Facilities					
Compressor Test Facility	60	--	Ambient	1	6 000 - 21 500
Compressor Research Facility	500	30 000	Ambient	1	2 000 - 3 000
Combustor Component Research Facilities					
Combustion Research Tunnel	7 1/2	N/A	Ambient	Atmoshperic	N/A
INDUSTRY					
Garrett Turbine Engine Company					
Turbine Component Research Facilities					
(Cooled) Hot Turbine and Cascade Test Facility	22	3 000	2 800	20	43 000
Cold Air Turbine Mapping Facility	6	400	600	125 psia	60 000
Compressor Component Research Facilities					
C-226 Compressor/ Fan Test Facility	30	600; 6 000	Atmospheric Inlet; 20 Exhaust	Atmospheric	85 000; 21 000
C-114, C-113 Compressor Test Facility	30	600; 6 000	Atmospheric Inlet; 20 Exhaust	Atmospheric	85 000; 21 000
Site A Fan Test Facility	180	8 000	Atmoshperic	2	11 000 - 21 000

PROPULSION COMPONENTS FACILITIES

FACILITY NAME/ LOCATION	MAX. FLOW RATE (lb/sec)	MAX. POWER (hp)	TEMPERATURE (^{o}F)	PRESSURE (atm. max)	SPEED (rpm)
Combustor Component Research Facilties					
C-100 Combustion Test Facility	18	N/A	60 - 2 000	20	N/A
General Electric					
Turbine Component Research Facilties					
Cell A7 Air Turbine Test Facility	70	15 000	100 - 1 000	8	15 000
Compressor Component Research Facilities					
Full Scale Compressor Test Large Fan Test Facility (FSCT/LFTF)	1700 fan/ 400 Compressor	48 000	-70 to Ambient	Atmospheric	4 000 - 15 000
Pratt & Whitney					
Turbine Component Research Facilties					
X-203 Test Stand	400; 125	10 000 - 20 000	-50 to +800	1.3;7 atm	600 - 15 000
X-212 Test Stand	225; 125; 84	4 000 - 10 500	+1200	2, 8, 9	5 000 - 15 000
Compressor Component Research Facilities					
B33A Stand	--	6 000	Amtient	Atmospheric	26 000
X-204 Test Stand	210; 400	21 600 max	-50 to +220	22.5"; 40" HgA	7 200 15 000
X-211 Test Stand	550	40 000	Ambient - 250	Atmospheric	5 000 - 10 989
Combustor Component Research Facilities					
High Pressure Combustor Lab	100	N/A	450 to 1 200	650 psia	N/A

PROPULSION COMPONENTS FACILITIES

FACILITY NAME/ LOCATION	MAX. FLOW RATE (lb/sec)	MAX. POWER (hp)	TEMPERATURE (^{o}F)	PRESSURE (atm. max)	SPEED (rpm)
Southwest Research Institute					
<u>Combustor Component Research Facilities</u>					
Army Fuels and Lubricants Lab, Combustor Test Facility	2.5	N/A	-65 to +1500	16	N/A
Telydyne CAE					
<u>Turbine Component Research Facilities</u>					
Hot Cascade Test Stand	2	N/A	3 000	7	N/A
Turbine 1 and Turbine 2 Cold Flow Rig	25	300; 2400; 450	Ambient - 300	1.7	45 000; 23 000; 11 500
<u>Compressor Component Research Facilities</u>					
3500 hp Compressor Test Stand	22	3 500	-60 to +110	1.5	39 000
1400-1 and 1400-2 Compressor Test Stands	22	1 200; 420	-65 to +235	1.5	42 000; 70 000
<u>Combustor Component Research Facilities</u>					
Combustor Cell	4; 22	N/A	-65 to +500	6; 1.7	N/A
Westinghouse Combustion Turbine Systems					
<u>Turbine Component Research Facilities</u>					
Vane Cooling Development Rig	90	N/A	2 200	20	N/A
Aerodynamic Cascade Test Rig Row One Turbine Vane	90	N/A	900	8	N/A

PROPULSION COMPONENTS FACILITIES

FACILITY NAME/ LOCATION	MAX. FLOW RATE (lb/sec)	MAX. POWER (hp)	TEMPERATURE (^{o}F)	PRESSURE (atm. max)	SPEED (rpm)
Compressor Component Research Facilities					
Combustion Turbine Development Center		25 000			12 000 - 4 100
Combustor Component Research Facility					
Full Scale Cylindrical Reverse Flow Rig	90	N/A	900	20	N/A
UNIVERISTY					
Massachusetts Institute of Technology					
Turbine Component Research Facilities					
Blowdown Turbine Facility	64 200 scaled	2 000 52 000 scaled	500 4 000 scaled	10 40 scaled	7 000 14 000 scaled
Compressor Component Research Facilities					
Blowdown Compressor Facility	100 scaled	--	212 (max)	1	22 000
JAPAN					
Ihi Mizuho Plant					
Turbine Component Research Facilities					
High Pressure Turbine Facility (HPT)	40	6 000	2 5000	3.5	15 000
Compressor Component Research Facilities					
Large Scale Aero Engine Compressor Facility	310	18 000	Ambient	2	13 000
Combustor Component Research Facilities					
Medium Pressure Combustor Facility (MPC)	24	N/A	180 to 780	7	N/A

C-3

PROPULSION COMPONENTS FACILITIES

FACILITY NAME/ LOCATION	MAX. FLOW RATE (lb/sec)	MAX. POWER (hp)	TEMPERATURE (^{o}F)	PRESSURE (atm. max)	SPEED (rpm)
National Aerospace Laboratory					
<u>Turbine Component Research Facilities</u>					
High Temp Turbine Cooling Facility	3.7	N/A	2 200	9	N/A
<u>Compressor Component Research Facilities</u>					
Fan/Compressor/ Turbine Facility	--	2 160	Ambient	Ambient	15 500
High Pressure Annular Combustor Test Facility	30	N/A	730	9	N/A
High Pressure Combustor Test Facility	8.8	N/A	Ambient - 850	50	N/A

APPENDIX

H

APPENDIX H

FLIGHT SIMULATION FACILITIES

CROSS INDEX

FACILITY NAME/LOCATION	SIMULATION	MOTION DOF	VISUAL	COMMENTS
NASA				
Ames Research Center				
Vehicle Specific Simulators				
Boeing 727 Flight Simulator	Boeing 727	6	Link & Miles Image II	Part of MVSRF
Generic Flight Simulators				
Advanced Concepts Flight Simulator	Advanced Aircraft LN 1995	-	Link & Miles Image II	Part of MVSRF
Flight Simulator for Advanced Aircraft (FSAA)	OSRA, RSRS, F111, Shuttle, KG135 UH60, UH-1H, XV15	6	Model Board/Calligraphic TV Camera	100 ft Lateral Motion
Vertical Motion Simulator (VMS)	Shuttle, XV15, UH60,	6	CGI, Full Color and Calligraphic	60 ft Vertical 40 ft Lateral Motion
6 Degrees of Freedom	-	6	TV Camera, Model Board	
Langley Research Center				
Airborne Simulators				
Terminal System Research Vehicle Simulator	Advanced Controls, Displays, Flight Management Systems	Full Fixed Base	All / Model; Board	1 Simulator in Air-craft; Identical Ground Based Simulator
High Performance Aircraft				
Differential Maneuvering Simulator	High Performance Aircraft and Helicopters	1 (buffet only)	Sky-Earth Transparencies Scale Model Targets	Dual Projection Domes for ACM
Vehicle Specific Flight Decks				
DC-9 Full Workload Simulator	Complete DC-9 with CDTI Display	Fixed Base	Model Board	Full Workload Cab

FLIGHT SIMULATION FACILITIES

FACILITY NAME/LOCATION	SIMULATION	MOTION DOF	VISUAL	COMMENTS
Generic Flight Decks				
Visual Motion Simulator	Variety of Aircraft	6	Model Board	
Mission Oriented Terminal Area Simulation (MOTAS)	Variety of Aircraft	-	ATC controller scopes	Air-traffic Control Simulator
Advanced Concepts Simulator	Advanced, all electric twin engine transport	Fixed Base	None	"All glass" Cockpit with Touch Panels and Voice I/O
Johnson Space Center				
Generic Flight Decks				
Systems Engineering Simulator	Space Shuttle	-	E & S CT3	
DOD				
Wright Patterson Flight Dynamics Lab				
Airborne Simulators				
NT-33A In-Flight Simulator	X-15, X-24, A-9, A-10 F-15, F-16, ATFI/F-16, F-18	3 Moments Only	Real World Vision	Model Follower Aircraft
NC-131H Total Inflight Simulator	B-1 Concorde SSt, YOM-98, Shuttle, X-29	6	Real World Vision	Model Follower Aircraft
High Performance Aircraft				
Large Amplitude Multimode Aerospace Research Simulator (LAMARS)	A-10, F-15, F-16, F-106, AFTI/F-16 X-29	5	Day, Dusk, Night Solid Model Terrain TV Projector	Projection Dome With Motion
Generic Flight Decks				
Fighter/Bomber Simulator	F-16	5	All, Solid Model Terrain Board	

FLIGHT SIMULATION FACILITIES

FACILITY NAME/LOCATION	SIMULATION	MOTION DOF	VISUAL	COMMENTS
Williams Air Force Base				
Generic Flight Decks				
Fiber-Optic Helment Mounted Display (FOHMD)	F-16C AT-38	Fixed	CGI	
24' Diam Limited Field of View Dome	F-16A with Block 10 and 15 Configurations	Fixed	CGI	
24" Diam Full Field of View Dome	F-16C	Fixed	CGI	
Low Altitude Night Terrain Infr-Red Navigation	F-16C	Fixed	CGI	
INDUSTRY				
Bell Helicopter				
Generic Flight Decks				
Engineering Interactive	XV15, JVX, LHX AH1, UH1, M222	Fixed Base	CGI	
The Boeing Company, WA				
Vehicle Specific Flight Decks				
737-300 Engineering Cab	737-300	Fixed	CGI with Multiple Windows	
Systems and Workload Cab	757, 767	-	CGI with Multiple Windows	
Flight Systems Laboratory	747	-	None	
Generic Flight Decks				
Multipurpose Cab	707, 727, 737, 747	3	CGI with Multiple Windows	
Boeing Vertol, PA				
Generic Flight Decks				
Engineering Flight Simulator Facility	Tandem Rotor, Tilt Rotor, Single Rotor	6	CGI with Multiple Windows	

FLIGHT SIMULATION FACILITIES

FACILITY NAME/LOCATION	SIMULATION	MOTION DOF	VISUAL	COMMENTS
Grumman Aerospace				
<u>Generic Flight Decks</u>				
Six Degress of Freedom Moving Base Simulator	X-29A, F-14, A-6	6	Model Board, Optical Probe, Color TV, Moving Target Model	Window or spherical screen
Crew Station Technology Lab	F-14, A-6, VSTOL	Fixed Base	Model Board	Partial Dome Projection
Large Amplitude Research Simulator (LARS)	VTOL	6	None	
Hughes Aircraft Company				
<u>High Performance Aircraft</u>				
Advanced Fighter Simulator	F/A-18, F-14 Rear Seater	Fixed Base	None	Heads Up and Heads Down Displays
Lockheed-Georgia Co				
<u>Generic Flight Decks</u>				
Man-Vechicle Systems Laboratory	Advanced Concepts Transport, Assualt Transport, C-130, C-5	6	Model Board, CGI with Multiple Windows	
Mc Donnell Aircraft Co				
<u>High Performanc Aircraft</u>				
Manned Air Combat Simulator #1, #2 #3, #4, #5	F-15, FA-18	Fixed Base	Day, Dusk, Color Multiple-Model Point Light Terrain Map or Flying Spot Scanner	Multiple Projection Domes for ACM
<u>Vehicle Specific Flight Decks</u>				
F/A-18 Developmental Simulator (MACS 3.5)	F/A-18	Fixed Base	CGI with Multiple Windows	
Manned Simulator VSTOL #1 (MSV-1)	AV-8B	Fixed Base	CGI with Multiple Windows	
Manned Simulator VSTOL #2	GR MK-V	Fixed	CGI with Multiple Windows	

FLIGHT SIMULATION FACILITIES

FACILITY NAME/LOCATION	SIMULATION	MOTION DOF	VISUAL	COMMENTS
Northrop				
<u>Generic Flight Decks</u>				
Large Amplitude Simulator (LAS)	Tactical Aircraft	5	Sky-Earth Transparencies Scale Model Targets	
Visual Flight Simulator (VFS)	Tactical Aircraft	None	Sky-Earth Transparencies Scale Model Targets	
Rockwell International				
<u>Vehicle Specific Flight Decks</u>				
Space Shuttle Hardware and Software Evaluators	Shuttle	Fixed Base	CBS Color Camera, Ferrand Optical Probe	
Sikorsky Aircraft				
<u>Generic Flight Decks</u>				
Fixed Base Simulator	Rotorcraft	Fixed Base	CGI	
Engineering Development Simulator	Rotorcraft	6	CGI	
CANADA				
NAE Flight Research Laboratory				
<u>Airborne Simulators</u>				
Airborne Flight Simulator	Rotorcraft and VSTOL Aircraft	4	N/A	
GERMANY				
<u>Airborne Simulators</u>				
Flying Simulator Helicopter Bo 105 S-3	High-Maneuverable Light Twin-engine	Full	Actual Flight (Real Workd)	Model Follower

FLIGHT SIMULATION FACILITIES

FACILITY NAME/LOCATION	SIMULATION	MOTION DOF	VISUAL	COMMENTS
Flying Simulator VFW 614 G-17 ATTAS	Advanced 2 Engine Jet	Full/ Fixed Base	Actual Flight (Real World)	Experimental Cockpit for Ground Base of Flight
<u>Generic Flight Decks</u>				
Air Traffic Management and Operations Simulator (ATMOS)	Advanced FBW Transport	-	ATC Controller Scopes	Air Traffic Control Simulator
JAPAN				
<u>High Performance Aircraft</u>				
Flight Simulator	All Types of Fighter Aircraft and VSTOL Transport	Fixed Base	Sky Earth Transparencies Scale Model targets	Single Projection Dome
<u>Vehicle Specific Flight Decks</u>				
Flight Simulator for Research & Development	Medium to Large Transports	6	CGI with Multiple Windows	
Flight Simulator	Advanced Technology Fighters	Fixed Base	CGI with Multiple Windows	
<u>Generic Flight Decks</u>				
Simulator for Aircraft Research & Development (SARD)	Advanced Fighter & Trainer Aircraft	Fixed	CGI with Multiple Windows	
NETHERLANDS				
<u>Generic Flight Decks</u>				
Moving Base Flight Simulator	Civil and Military Single/Twin Engine Aircraft	4	Model Board	

1. Report No. NASA RP-1146	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Aeronautical Facilities Assessment		5. Report Date November 1985 6. Performing Organization Code Code R
7. Author(s) Frank E. Peñaranda, Compiler		8. Performing Organization Report No.
9. Performing Organization Name and Address National Aeronautics and Space Administration Office of Aeronautics and Space Technology Washington, D.C. 20546		10. Work Unit No. 11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report and Period Covered Reference Publication 14. Sponsoring Agency Code

15. Supplementary Notes

Companion report to NASA RP-1132 and 1133, Aeronautical Facilities Catalogue

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16. Abstract

A survey of the free world's aeronautical facilities was undertaken and an evaluation made on where the relative strengths and weaknesses exist. Special emphasis is given to NASA's own capabilities and needs. The types of facilities surveyed are: Wind Tunnels, Airbreathing Propulsion Facilities, and Flight Simulators.

17. Key Words (Suggested by Author(s)) aeronautical facilities, assessment, foreign facilities, wind tunnels, aeropropulsion, flight simulators, engine test facilities, propulsion, component	18. Distribution Statement [redacted] [redacted]

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 201	22. Price